NAVAL
POSTGRADUATE
SCHOOL

MONTEREY, CALIFORNIA

THESIS

AN OPTIMIZATION MODEL FOR FIBER-OPTIC CABLE INSTALLATION ABOARD NAVAL VESSELS

by

David S. Dorfman
Frank A. Strom III

June 2013

Thesis Advisor:	Fotis Papoulias
Co-Advisor:	Diana Angelis

Approved for public release; distribution is unlimited

THIS PAGE INTENTIONALLY LEFT BLANK

REPORT DOCUMENTATION PAGE			*Form Approved OMB No. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.			
1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** June 2013	**3. REPORT TYPE AND DATES COVERED** Master's Thesis	
4. TITLE AND SUBTITLE AN OPTIMIZATION MODEL FOR FIBER-OPTIC CABLE INSTALLATION ABOARD NAVAL VESSELS			**5. FUNDING NUMBERS**
6. AUTHOR(S) David S. Dorfman, Frank A. Strom III			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol number ____N/A____.			
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited			**12b. DISTRIBUTION CODE**

13. ABSTRACT (maximum 200 words)

The purpose of this thesis is to develop a cost-optimization model that will help reduce the installation cost of fiber-optic cable onboard new construction naval vessels. The data used to develop the optimization models were collected from visits to naval shipyards and interviews with both fiber-optic cable engineers and installation experts at shipyards, as well as MIL-PRF 85045F and cable manufacturers' specification sheets. The information compiled from these sources was used to develop a cable measure of effectiveness that could be inputted into simulation software. Simulations were run to examine the effect of cable quality, quantity, and labor rate in order to select the best fiber-optic cable for installation based on cost risk. Depending on the specifics of a fiber-optic cable run, cable choice can vary, but in general the cable with the highest quality results in a lower risk of cost overruns and is the most cost effective choice over the long run. Program managers and shipyards can easily implement the models developed in this thesis into their current practices for fiber-optic cable procurement and installation aboard U.S. naval vessels.

14. SUBJECT TERMS Systems Engineering, Optimization Models, Fiber-optic Cable, Ship Construction, Ship Maintenance, Power, Energy, Naval Architecture			**15. NUMBER OF PAGES** 89
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UU

NSN 7540-01-280-5500 Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

THIS PAGE INTENTIONALLY LEFT BLANK

Approved for public release; distribution is unlimited

AN OPTIMIZATION MODEL FOR FIBER-OPTIC CABLE INSTALLATION ABOARD NAVAL VESSELS

David S. Dorfman
Lieutenant, United States Navy
B.S., United States Merchant Marine Academy, 2009

Frank A. Strom III
Lieutenant, United States Coast Guard
B.S., Massachusetts Maritime Academy, 2005

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN SYSTEMS ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
June 2013

Authors: David S. Dorfman
Frank A. Strom III

Approved by: Fotis Papoulias
Thesis Advisor

Diana Angelis
Thesis Co-Advisor

Clifford Whitcomb
Chair, Department of Systems Engineering

THIS PAGE INTENTIONALLY LEFT BLANK

ABSTRACT

The purpose of this thesis is to develop a cost-optimization model that will help reduce the installation cost of fiber-optic cable onboard new construction naval vessels. The data used to develop the optimization models were collected from visits to naval shipyards and interviews with both fiber-optic cable engineers and installation experts at shipyards, as well as MIL-PRF 85045F and cable manufacturers' specification sheets. The information compiled from these sources was used to develop a cable measure of effectiveness that could be inputted into simulation software. Simulations were run to examine the effect of cable quality, quantity, and labor rate in order to select the best fiber-optic cable for installation based on cost risk. Depending on the specifics of a fiber-optic cable run, cable choice can vary, but in general the cable with the highest quality results in a lower risk of cost overruns and is the most cost effective choice over the long run. Program managers and shipyards can easily implement the models developed in this thesis into their current practices for fiber-optic cable procurement and installation aboard U.S. naval vessels.

THIS PAGE INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

LIST OF FIGURES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF TABLES

THIS PAGE INTENTIONALLY LEFT BLANK

LIST OF ACRONYMS AND ABBREVIATIONS

CNO	Chief of Naval Operations
CoQ	Costs of Quality
DoD	Department of Defense
GUI	Graphical User Interface
LHA	Amphibious Assault Ship
LSW	Light Ship Weight
MIL-PRF	Military Performance Specification
MIL-STD	Military Standard
MILSPEC	Military Specification
MOE	Measure of Effectiveness
SME	Subject Matter Expert
WBS	Work Breakdown Structure

THIS PAGE INTENTIONALLY LEFT BLANK

EXECUTIVE SUMMARY

In 2005, then Chief of Naval Operations Admiral Vernon Clark testified to Congress that U.S. Navy ship costs are increasing at a rate that exceeds inflation. As a result it is becoming more difficult for the government to afford the ships it requires in the fleet and meet the requirements expected of said fleet. Leaders understand that new processes and improvements must be developed and implemented, by the Navy and contractors alike, in order to achieve the strategic requirements the future Navy will need and government leadership will demand. Cost-optimization modeling is one method to help incrementally improve the future of naval shipbuilding. These incremental improvements, in the aggregate, will help leadership meet the future goals of the U.S. Navy.

This thesis develops a cost-optimization model that evaluates the cost of fiber-optic cable for installation on a ship based on cable specifications provided by the manufacturer. The model is used to evaluate four different fiber-optic cables based on the cost of installation in terms of materials and labor. Military branded fiber-optic cables are designed and manufactured following MIL-PRF 85045F. This military specification (MILSPEC) is designed to give minimum requirements for fiber-optic cable and does not incentivize cable manufacturers to create fiber-optic cable that exceeds this quality. Several visits to naval shipyards revealed that a common problem amongst all shipyards was fiber-optic cable installation. The delicacy of fiber-optic cable often results in damaged cable that must be reinstalled (rerun). In an effort to improve the shipbuilding process, the model in this thesis provides a decision maker with a tool to help select a particular cable amongst of group of similarly specified cables.

Two types of models were developed in this thesis. The first model examined cable specifications in order to develop a measure of effectiveness (MOE) for a particular cable. It then utilized the cable's MOE to quantify the probability of success in a geometric distribution and to calculate the expected number of runs that would be required to successfully install a particular cable with 99% certainty. This value was then used to calculate the expected cost of installation and to quantify the risk of a cost overrun for a given level of funding.

The second model used the parameters developed in the first model in several simulations. The benefit of the simulation model is the ability to incorporate time and cost variances into the simulation. In particular, time uncertainty (labor hours) that follows a beta distribution was introduced into the model. This provides a more realistic simulation for cable selection. The simulation model parameters were varied to perform a sensitivity analysis to examine the effects of labor cost on the overall cable selection.

In this thesis, four varieties of a specific type of fiber-optic cable were analyzed. The results of the analytical model show that the cable with the highest MOE would be the best choice for installation due to the fewer number of reruns. The simulation model was validated using these results. The addition of time uncertainty based on a beta distribution suggests that depending on the budget available for installation, a higher MOE cable may not always be the best choice. The results of the sensitivity analysis on labor rates support this finding, although the expected costs were always lowest for the cable with the highest MOE.

Naval vessels are becoming increasingly more technologically dependent and capable. As these dependencies and capabilities grow in parallel with the rising costs of shipbuilding, cable installation becomes more important than ever before. The optimization analysis and methodology performed in this thesis serve as a good starting point for improving cable installation processes during ship construction in the U.S. Navy and U.S. Coast Guard.

ACKNOWLEDGMENTS

We would like to thank Dr. Fotis Papoulias and Dr. Diana Angelis for their time and mentoring throughout our work on this thesis. We also would like to thank Professor William Solitario for his guidance, contacts, and shipyard industry knowledge that was paramount to our research. We thank Captain Chris Meyer (PMS 378) for his inspiration on this thesis as well as the various shipyard employees who provided their invaluable knowledge and expertise.

Finally, we would like to thank our parents, Frank, Susan, Bruce, and Suzanne, for their love and support during our time at the Naval Postgraduate School. A special thanks to Barbara Berlitz and Mikel Strom for their editing expertise and proving to us once again that engineers have a poor command of the English language.

THIS PAGE INTENTIONALLY LEFT BLANK

I. INTRODUCTION

Over the past four decades, U.S. Navy ship costs have exceeded the rate of inflation. In 2005, the former Chief of Naval Operations (CNO), Admiral Vernon Clark, testified in front of Congress noting the cost increases to nuclear attack submarines, guided missile destroyers, amphibious ships, and nuclear aircraft carriers. The rise in cost varied for each ship class between 100 to 400 percent (Arena 2006). Modern-day naval vessels have become increasingly more complex, resulting in these higher costs. A 2006 study by the RAND Corporation for the CNO revealed that light ship weight (LSW) and a ship's power density, or power generation capability compared to the LSW, correlated strongly to total ship cost (Arena 2006). This is because the number of mission systems on naval vessels has increased and the desire for more complex ships has been a significant cause of ship cost escalation in recent decades (Arena 2006).

Comments from PMS 378, the Program Manager for Future Construction Aircraft Carriers, made it clear that ship production costs were rising, but that there were opportunities to improve the shipbuilding process. These improvements would ultimately result in cost reduction and a more efficiently built ship. During a teleconference with PMS 378 multiple areas for improvement were discussed. The cable laying process in particular was identified as an area that had a tremendous amount of room for improvement. As the RAND Study highlighted, the more technologically advanced ships found in the U.S. Navy of the 21st century required complex electrical systems. The cable laying processes and efficiency would be paramount to successful builds.

A. PROBLEM STATEMENT

As the costs for naval vessels escalate it becomes imperative to research methods that may help reduce the final cost to the government. Today's ships are becoming increasingly complex and more advanced than ever before. The cutting edge technology found in these ships requires more fiber-optic cable to transfer data and information. The difficulties of running fiber-optic cable during construction are an area that can be improved. Given present shipyard construction practices, it is difficult to monitor cable

installation processes. However, the methodology for fiber-optic cable selection can be improved and this thesis will address an optimal method for selecting fiber-optic cable.

B. RESEARCH QUESTIONS

Three questions will be addressed in this thesis:

- Is the total cost of installation less for running higher quality fiber-optic cable over a baseline MILSPEC version?
- Are the cost savings great enough to specify a higher quality cable?
- What's the relative cost risk presented by cable types?

C. BENEFITS OF STUDY

There are several benefits of study for this thesis. The first benefit of the study is to improve fiber-optic cable selection methods. To save on cost, human intuition drives the selection of the least expensive cable, but sometimes this is a nearsighted assumption that results in cost and schedule overruns. The study will also aid in developing a modeling and simulation philosophy for selection of all cable types. The processes and methods developed will be translatable to cables other than fiber-optic. By improving cable selection, cable installation will be more efficient. These gains will be realized during scheduling improvements. Most importantly, the study will benefit decision makers by providing them with a tool from which they can best select a particular fiber-optic cable.

D. SCOPE AND METHODOLOGY

The scope of this thesis is limited to the material and labor costs associated with fiber-optic cable installation. A measure of effectiveness (MOE) is developed based on cable characteristics relevant to installation only. This MOE is used as a proxy for the probability of success in a geometric distribution and then incorporated into a simulation model to determine the optimal cable based on run time, cost, and cable quality. This thesis will not examine certain factors that are part of the cable laying process such as labor skillset, fiber-optic cable variety, and installation techniques (mechanical vs. manual labor).

Chapter II of this thesis will examine current-day shipbuilding processes including the various types of modern ship construction and their impacts on cable installation. In Chapter III fiber-optic cable installation will be discussed, including the basics of fiber-optic cables and installation issues. The observations made during visits to three different U.S. shipyards are reported, including how rework of cable can impact cost. The model development will be discussed in Chapter IV including the modeling approach and philosophy, the development of the MOE, and the design of our simulation. Chapter V provides the results of the analysis using analytical and simulation models and discusses the cost risk implications of these results.

THIS PAGE INTENTIONALLY LEFT BLANK

II. CURRENT SHIPBUILDING PROCESS

A. MODERN-DAY SHIP CONSTRUCTION

Prior to modern-day shipbuilding, a ship's construction began when the keel was laid with all other construction connected to the keel as the ship was subsequently built up. This process stemmed from the construction of wooden sailing vessels. As steel ships became larger and more complex around the time of World War I, this process that worked well for wooden ships, became inefficient and outdated. These vessels now incorporated more piping and electrical systems because they were larger than their predecessors. The outfitting of compartments within the ship was a slow process in keel up construction because compartments were not prefabricated. This required workers to walk in all piping and cabling after the internal compartments were structurally created to support these systems.

By World War II, the ship building industry around the world had greatly increased in support of each nation's navy and merchant marine. Modular construction, or the process of building individual three-dimensional blocks that integrate to form a ship during erection, was adopted and refined by the Japanese. It was not until the 1960's that the United States introduced the Japanese shipbuilding method to its own shipyards (Bill Solitario 2009). This new form of ship construction proved to be vastly superior to keel up construction for several reasons. The first reason is there are efficiencies gained when combining modular construction and zone outfitting. Zone outfitting is a shipbuilding system that enables outfitting of each block with machinery, cable, piping, etc. prior to its addition to the other blocks. These efficiencies are realized because of the open nature of assembling one block at a time. These processes combined vastly improve overall shipbuilding efficiency. The second reason is that this new form of construction proved to be less structural in nature. Wooden ship structure consisted of a framework or skeleton of transverse frame rings girding the ship, connected longitudinally by a massive timber keel structure. As steel shapes came about, the number of structural members to provide equivalent strength to their wooden counterparts was fewer. All material no longer was tied into a single structural member: the advent of block construction was realized (Zubaly 1996).

B. GRAND BLOCK CONSTRUCTION

Block construction utilizes segmented sections of the ship that join together to form the hull and surrounding super structures. The grand block construction technique incorporates two or more blocks being joined together. These grand blocks are joined to other grand blocks. This is an advantage because it allows local piping and cabling systems to be outfitted within the grand block before it is connected to the rest of the ship. Grand block construction was not possible until the introduction of heavy lift cranes in shipyards that were capable of moving and positioning these large sections easily. One of the most beneficial aspects of grand block construction is the ability to flip grand blocks upside down and fabricate overhead portions of the block. This prevents shipyard workers from working overhead which is difficult and time consuming. A positive consequence of this fact is a reduction in time and increased ability to lay cable.

C. SUPERGRAND BLOCK CONSTRUCTION

Supergrand block construction is a more recent form of modular ship construction where a series of grand blocks are joined together. This allows for more outfitting, in addition to local piping and cabling, before the ship is launched. Cable and piping sections would be spliced and joined at supergrand block edges. This reduces the number of final blocks that are connected. An example of supergrand block construction can be found at Huntington Ingalls Industries Shipyard in Pascagoula, Mississippi. The construction of the latest LHA was done in three supergrand blocks; the forward end, the after end, and the superstructure island. These three pieces were then joined prior to the vessel's launch.

D. THE IMPACT OF CONSTRUCTION PROCESS ON CABLE INSTALLATION

The outfitting of cable and piping systems on ships differ in that it is acceptable to stop and start piping systems where blocks end, whereas it is preferable to continuously run cable for as long as possible. Cables can experience power drops and poor attenuation when constantly cutting the cable and splicing it back together. Comparatively, piping does not experience these performance losses.

There are several advantages to laying cable on ships utilizing block construction. These advantages are realized between the performance characteristics of the cable and the manner in which cable is laid. All shipboard cable is laid by hand, and the majority of cable is pulled without machinery or other mechanical advantage (Anonymous Person A 2012). The lack of machinery and automation for laying cable makes the entire process arduous.

One of the primary advantages of block construction is the ability to load cable rolls onboard more easily. This prevents dropping cable by hand into the ship once it has been launched. As an example, in block construction, even if a block is not ready for the cable to be laid yet, the shipyard workers can still preposition the cable roll inside the block for it to be laid up later. Electrical cabling can be laid both locally, within a block or grand block, or throughout the ship. Cable that passes throughout the ship is known as main cable. Local cable can be laid in grand block construction effectively at any time, but main cable is laid more effectively in supergrand block construction because longer cable runs are possible.

As previously mentioned, the ability to flip blocks and grand blocks upside down improves the efficiency of both outfitting and fabrication processes. Since most electrical cable is laid in compartments overhead, it is therefore easier for the shipyard to install cable while the compartment is inverted. This is because of cable weight and the reach required by the workers. Shipyards commonly utilize a rule of thumb known as the '1-3-8' ratio. This ratio translates as follows; one hour of work in the shop, three hours of work in the dry dock, and eight hours of work once the ship is in the water (Bill Solitario 2009). This ratio is derived from prior experience of shipyard workers. The more outfitting accomplished on land, the less man-hours utilized once the ship is in the dry dock or water.

The size and magnitude of a modern naval vessel requires shipyards use robust but complex tracking systems to follow the construction of each vessel. A work breakdown structure (WBS) will aid in classifying and sub-dividing the individual work required for ship construction. The above-mentioned forms of modular construction are easily integrated into a WBS because individual models can be allocated to a specific part of the WBS. This is the basis for scheduling cable runs in the various block, grand block, and supergrand block assemblies.

Modular construction is proven to be the most efficient and effective means for constructing large-scale naval vessels. The complexity of these projects and the systems within the ship's hull necessitate the requirement for modular construction and zone outfitting. By building the ship in modules, different parts of the ship can be built at different times or simultaneously to help reduce the project's overall time and eliminate potential work stoppages due to the independent nature of each module. This construction methodology greatly improves the overall cable laying process. With future generations of naval vessels requiring more cable on ships due to their increasingly complex electrical systems, efficiently laying cable has never been more important. The next chapter will discuss the specific philosophies of laying cable on naval vessels.

The following chapter will discuss the current installation procedures of fiber-optic cable at various United States private shipyards. The discussion that follows offers evidence for an in-depth look into potential efficiencies that can be realized regarding fiber-optic cables installation on naval vessels. This will provide a foundation for the modeling, simulation, and analysis performed later on.

III. FIBER-OPTIC CABLE INSTALLATION

A. FIBER-OPTIC CABLES

Modern-day naval vessels are outfitted with complex machinery and weapon systems and are steadily being pushed towards all electric ships that require more power and communication cabling. Fiber-optic cable was developed during the latter part of the twentieth century and has many advantages over conventional copper cable. The biggest advantage of fiber-optic cable is its effectiveness in transporting information. Fiber-optic cable can transport more information over longer distances faster than any other communications conduit. Fiber-optic cable is lightweight and smaller than copper cable making it ideal for use on naval vessels where space is at a premium. The high bandwidth capabilities of fiber-optic cable reduce the number of cables required to achieve the same transmission volume (Hayes and Fiber-optic Association 2009).

Fiber-optic cable on United States naval vessels is held to a military performance specification or MIL-PRF. The governing standard is MIL-PRF-85045F. This specification was authorized on August 12, 1999. The Commander of Naval Sea Systems Command (SEA 05G), DoD Standardization Program and Documents Division, Department of the Navy controls this specification even though it is approved for use by all DoD agencies and departments. This is the standard that fiber-optic cable must be built to for installation onboard naval vessels.

B. INSTALLATION ISSUES

For our thesis research, we visited several U.S. naval shipyards in order to gain a better understanding of fiber-optic cable installation during the new construction process of naval ships. During these visits, we consulted with the shipyard's subject matter experts on cable installation as to their philosophy on the installation of fiber-optic cables. While each shipyard was held to the same military standard and specifications as set forth by the DoD, each shipyard's overarching view of fiber cable installation from "cradle to grave" varied widely.

1. Site Visit A

The first site visited built both naval and commercial ships and expressed the challenges associated with building naval vessels due to the increased amount of cable onboard. Site A felt it best to have a high material availability at the beginning of construction because it prevents delays due to late shipment of materials. This practice is sound if the build schedule is not excessively long and there are adequate storage facilities on site to house all materials purchased. It was noted that this up front method is not always practical at all naval shipyards due to real estate restrictions, complexity of some naval vessels, and a prolonged build schedule for these more complex ships.

This site improved its construction timelines through proper planning and personnel promotion. The shipyard strove to achieve an extremely high percentage of engineering and construction drawings complete before construction begins. They did note that this completion percentage can fluctuate greatly on the first hull of a series but is reduced considerably for follow on hulls. It also assumes that the Navy does not ask for wholesale changes for the later hulls. Promoting experienced shipyard employees was another important aspect of site A's model that improved the construction process. The employees who have experience laying cable have a better understanding of the cable laying process than the naval architects and engineers who design the cable runs. They help to expedite the running of cable during construction and will perform a reroute on the spot if they realize it will be a more efficient means of running the cable. This rerouting of the cable will then be used for follow on hulls. This real time change of cable run reduces the amount of cable used, but it requires skilled workers with high experience levels. They noted that this might be a more difficult concept to implement on larger more complex naval platforms due to the lack of space for running cable and because cableways are usually run to maximum capacity on the more complex platforms.

Site A utilizes grand block construction. Modules are made into grand blocks, which are then lowered into the dry dock and welded together to form the ship. The two greatest limitations in this process are crane lifting capacity and dry dock space. The shipyard's crane capacities will dictate the size of each grand block and how much cable laying and outfitting can be completed. Sometimes ships are launched earlier than what

would be considered the optimum time due to the size of the ship. If the dry dock cannot support the full ship, it will need to be launched early.

Cable laying at Site A begins with the planning process. This tracks where and when each cable must be laid on the ship. A robust planning model is in place and must be carefully followed. All cable must be laid in advance of the painting schedule and any delays must be rapidly identified and adjusted for. Cable is delivered and stored at the shipyard at the beginning of construction, and cables are stored with other cables that will be laid in the same compartments onboard the ship. If cable is laid after launch, it is raised onto the ship within a large basket. There is a cable tracker system in place that is responsible for tracking the cable from "cradle to grave." During installation the cable is color-coded by the shipyard, and the installation progress is logged daily. Once a cable is run, each end is to be tagged. This tag informs the other shipyard workers responsible for hooking the cable to equipment that it was ready to be connected.

Site A was the only site that used mechanical cable pullers for large power cables, and did not use junction boxes for long runs of cable. Instead the shipyard workers ran long runs of wiring which could be an area for improvement. Their greatest advantages were real time modifications to cable laying routes and a reduced learning curve between hulls.

2. Site Visit B

The visit to Site B provided an up close look at a large-scale naval vessel under construction. The ship being constructed had several million feet of cable installed, considerably more cable than found at Site A. The vessel being constructed was being built utilizing supergrand block construction techniques. According to the shipyard managers, the supergrand block construction had been a great success over their grand block construction process because it accelerated outfitting and cable laying. Long cable runs were joined at junction boxes where the supergrand blocks were connected. Many workers at Site B felt that running cable was the single most difficult job during the construction of a ship.

The biggest issue noted by Site B was the procurement of cable that was the baseline acceptable military specification cable. This cable, while meeting specifications

as outlined by the DoD, often became broken and damaged. The cable was being damaged in the harsh work environment that exists in the construction of a naval vessel. Cable failures resulted in the removal and rerunning of a new cable, sometimes with the same result, and it was not uncommon for a cable to be run six to seven times before a successful run was performed. The managers advocated for higher quality cable that exceeds the military specification standards, especially for fiber-optic cable because it is more fragile and expensive than regular copper cables.

The cable at Site B is entirely pulled by hand. They believed cable-pulling machines were counterproductive and caused more harm than good resulting in more rework. The larger amounts of cable on the ship at Site B meant more cable in the wireways overhead. Using a machine to pull cable tended to damage the surrounding cables.

One of the most impressive components of Site B's cable installation process was their real time tracking system. When a cable arrives at the shipyard its barcode is scanned via a hand held tracker. Once the shipyard workers are ready to run the cable it is brought over from storage and loaded onto the ship or module (depending on the phase of construction). While the cable is being laid it is scanned at regular intervals and progress can be monitored against the planned schedule. If a cable breaks during installation, the supervisors know immediately how far along the cable is in the installation process and how much more work they will need to plan for rerunning the cable.

Site B utilizes "just in time" ordering philosophy for all cable that is laid onboard. The basic principle behind the ordering philosophy is to receive the cable approximately 60 days prior to scheduled installation on the ship. No major delays have been experienced due to unavailability of cable. The reason for this approach is the long time duration required to build the more complex naval vessels and storage restrictions. Unlike Site A, the ship being built at Site B was more complex and would require several years to build. Storing cable for long periods of time would require a lot of money upfront and risk the cable being damaged while in storage.

The real time cable tracking system and supergrand block construction process were the greatest advantages of Site B.

3. Site Visit C

The final shipyard, Site C, builds extremely large naval vessels. During our visit, it was obvious that larger and more complex ships were more problematic for outfitting and laying cable. Additionally, the vessel being constructed was also the first hull of its class. In general, shipyards aim to accomplish as much cable laying and outfitting as possible before a ship is launched. On this vessel the shipyard was aiming for two-thirds of outfitting complete before launch but fell short of their goal, reaching only into the high fifty percent.

Site C was the least efficient yard when it came to preloading cable onto grand blocks for construction or even onto the super grand blocks that are eventually assembled. This resulted in long lag times for cable installation because it was "walked" into the ship from the top decks down. With close to ten million feet of cable to install, this became a major backlog during construction.

The cable tracking system at Site C was poor and ineffective in comparison to Sites A and B. Larger amounts of cable dictate a more robust cable tracking system, but this was not present. Site C lacked the refinement of Sites A and B in their cable laying process. This is due to the large size of the vessel and to being the first hull of its class.

C. COST AND REWORK

The installation of cable on vessels in a shipyard can be tedious and backbreaking work. Fiber-optic cable installation, while not as physically demanding as conventional power cable installation, presents a myriad of problems that can quickly inflate ship production costs. The major installation problems and their effect on rework will be discussed in this section.

The first major problem with installation of fiber-optic cable when compared to power cable is that it cannot be easily repaired. During the installation process for fiber-optic cable, when cable damage is discovered, it must be uninstalled. An issue that exacerbates the problem of repairing fiber-optic cable is that it is hard to precisely identify the section of the fiber-optic cable that has been damaged. Even if that section could be positively identified, it is hard to repair fiber-optic cable and not time efficient to

do so (Anonymous Person A 2012). Not being able to repair damaged fiber-optic cable means that when installed cable is deemed damaged and unusable, it has to be entirely replaced with new fiber-optic cable.

The complete testing of fiber-optic cables during installation is time consuming, difficult, and is often not done. Shipyards perform two main tests to check the effectiveness of fiber-optic cable during installation. These tests are a light test and a load test. The light test checks to see that the cable is transmitting light throughout the run and the load test ensures that the cable can perform its end mission by being hooked up to the equipment it will support. Both of these tests can take upwards of an hour a piece to run; therefore, they are not usually preformed at short intervals (or at all) during a long cable installation. Our research found that yards would periodically adjust this policy if a batch of cable from a manufacturer was not installing well. As an example, one shipyard attempted to install a 1000-foot run of fiber-optic cable three times before finding out at the end of each installation that the cable was bad. On following runs, after the third attempt, the shipyard took time to check the installation at 200-foot intervals. Even with testing at 200-foot intervals it took the shipyard seven runs to successfully install the 1000-foot run. The cost and schedule impact of this was significant and highlights the difficult task of installing fiber-optic cable onboard ships. The main reason cited by the shipyard SME for the multiple runs of fiber-optic cable during the 1000-foot run was poorly manufactured cable from the supplier.

1. Schedule and Cost Impacts

Examining the 1000-foot cable installation example described above is a good way to look at the effects of fiber-optic cable installation and rework on schedule. The financial impacts of rework are notionally considered because shipyard labor costs are business sensitive and were not provided by the shipyards.

To run 1000 feet of fiber-optic cable on a ship takes a six-person crew two full workdays to install. This time does not include periodic testing of the cable. With periodic testing of the cable included this would take an additional half-day bringing the

total time to two and a half full workdays. To fully uninstall 1000 feet of fiber-optic cable it takes the same six-person work crew upwards of eleven hours.

These times are not constant and can change dramatically based on when and where the ship is on the construction process. As an example, if a space has been turned over to the buyer, and it is found that the fiber-optic cables in that space has been damaged, it will take significantly longer to replace that cable. The main reasons for the extended replacement time is that the cable in a space turned over to the buyer is bundled to other cables and those cables, if passing through an air-tight or water-tight bulkhead, are packed inside conduit with rubber caulking to prevent the egress of water. These issues extend the installation process and present the additional problem of damaging good cable.

According to shipyard fiber-optic cable SME's; the biggest cost and schedule problem is reworking cable after a space has been turned over to the buyer. Reworking cable in these spaces is far more difficult and often results in having to preform additional maintenance in the space like re-painting. The cost associated with this kind of rework is not directly proportional to performing rework on the same space before it had been turned over to the buyer. The most cited reason for having to do repair in these spaces was the quality of the cable installed. Substandard cable has the tendency to fail after it has been successfully installed if the weight of the surrounding cable becomes too great. The outer sheathing of the substandard cable will often give way under the weight of surrounding cable and will cause the enclosed glass fiber to crack and fail. These issues typically are not discovered until late in the construction process and are often the most costly to repair.

Throughout all of the site visits, a common theme emerged with regards to naval vessel construction: running any type of electrical cable was an arduous task if not the single most difficult task performed by the shipyard workers. Regardless of the extreme difficulty in running cable, the shipyard workers and engineers see room for improvement. A realistic area for improvement exists in the running of good quality fiber-optic cable. The model development introduced below will outline one approach at improving fiber-optic cable running onboard naval vessels.

THIS PAGE INTENTIONALLY LEFT BLANK

IV. MODEL DEVELOPMENT

A. MODELING APPROACH AND PHILOSOPHY

The principal question that drove modeling was this: is the total cost of installation less for higher quality fiber-optic cable than a baseline MILSPEC version? While fiber-optic cable installed on naval vessels is made with respect to MIL-PRF-85045F, cables made by different manufacturers have slightly different specifications that can affect its durability during installation. Contracts between the contractor and the Navy require the use of military specification cable but do not stipulate from which supplier the cable must come. This allows shipyards to purchase fiber-optic cable at the lowest price point, which makes financial sense upon initial investigation. However, when a cable is rerun several times because of poor installation characteristics, it may no longer make financial sense to use the least expensive cable, particularly if the less expensive cable requires more rework. Achieving a high level of quality within a product, in this case fiber-optic cable, is typically promoted by the shipyard because it is of important value to the U.S. Navy. Unfortunately, a higher quality cable can cost more for the shipyard and reducing the overall fiber-optic cable costs while simultaneously increasing the cable quality is only possible if the costs of quality (CoQ) can be identified and measured (Schiffauerova and Thomson 2006). CoQ is usually understood as the price paid for prevention of poor quality (conformance) plus the cost of poor quality caused by the product failure such as rework (non-conformance). Examining the tradeoffs between the level of conformance and non-conformance costs are essential in helping to reduce rework and improve one’s bottom line (Schiffauerova and Thomson 2006).

Following visits to shipyard sites A, B, and C, it became a common theme among each shipyard’s electrical cable installation teams, that fiber-optic cable of higher quality and consequently higher cost, tended to be installed successfully after a fewer number of runs or even only one run. In an interview with one subject matter expert, it was quite clear that the shipyard procured a cable that adhered to MIL-PRF-85045F, but it failed to be installed successfully on a regular basis until the sixth or seventh time. After these

successive failures, the SME was able to convince senior shipyard employees that a higher quality cable would save time and money.

While it was evident to the above mentioned SME that a higher quality cable would produce better installation results, the specific answer as to why was not as clear. Fiber-optic cable manufacturers test their cables to the mechanical and environmental performance requirements in MIL-PRF-85045F. A short survey was conducted to see which military specification requirements drove successful cable installation. This was done to provide us with a rudimentary understanding of what particular specifications would be most applicable to fiber-optic cable installation and help create a sound measure of effectiveness. The survey instrument, along with full results, are available in the appendix. The survey results showed that mechanical performance requirements were more important than environmental performance requirements. They also demonstrated that among environmental performance requirements, temperature cycling and temperature humidity cycling requirements were equally important. Lastly, the survey respondents believed that the order of importance of the mechanical performance requirements with respect to fiber-optic cable installation were as follows from most important to least important: cable twist-bending, impact, crush, cable element removability, operating tensile load, tensile loading and elongation, cyclic flexing, knot, and low temperature flexibility. After receiving and analyzing the results of our survey, we contacted a fiber-optic cable engineer to further discuss our results. It became quite clear that there were only three specifications within MIL-PRF-85045F that would improve cable installation if these particular specifications required a higher standard. The three specifications: tensile strength, minimum bend diameter, and crush, will be discussed in further detail later in this chapter.

B. MEASURE OF EFFECTIVENESS

1. Overview

To estimate the installation quality and estimate the level of rework for fiber-optic cable, a simple model based on certain characteristics of a fiber-optic cable was developed. The model was used to evaluate the various brands of a specific fiber-optic

cable type and estimate the percentage of rework that can be expected for each cable based on its specifications. Higher MOE corresponds to a higher quality cable that would have a lower probability of requiring rework after installation. This will allow the end user (shipyard, contractor, program office, etc.) to evaluate different cables based on the expected rework. Ideally this model could be of use for all types of fiber-optic cable and with slight modifications, as will be seen later, with power cable as well.

Next, the MOE was used to estimate the probability of failure for each cable alternative based on a linear relationship. The number of failures was modeled using a geometric distribution with the probability of failure given by the MOE model. The geometric distribution was used to determine the probability that a cable would be successfully installed in N runs. These probabilities were then combined with the cable cost to calculate the expected cost of running the cable at various lengths and the trade space for selecting a particular cable type/brand for a project.

The initial development of this MOE model was accomplished by dissecting MIL-PRF-85045F. A subject matter expert suggested ideas for selection of the specifications that were judged to be most important to the installation of a fiber-optic cable and most related to the need for rework after initial installation. These specifications were tensile strength (in newtons), minimum bend diameter (in inches), and crush (in newtons). Although there may be other specifications that would also influence the amount of rework, the amount of information available from the manufacturers limited factors for consideration. The tensile strength specification is the value that represents the highest load that can be placed upon a cable before any damage occurs to the fibers or their optical characteristics (Cables Plus USA). Typically manufacturers will specify an installation tensile strength value and a long term tensile strength value with the installation value being higher. This is due to the increased stresses placed on the cable during installation as it is pulled. The minimum bend diameter specification is the value that represents the smallest bend a cable can withstand. Beyond this limit there could be an increase in fiber attenuation resulting in poor performance (Cables Plus USA). Again, during installation the cable is under more stress which results in a larger minimum bend diameter over the long term minimum bend

diameter. After the cable has been installed and the installation stresses removed, a smaller diameter may be used. The final specification, crush, specifies the maximum compressive loading the fiber-optic cable can withstand in newtons before there are unacceptable attenuation losses. This is important because fiber-optic cables can be run in the same wireways or trays as heavier power cable (Cables Plus USA).

2. Specification Value

While discussions with the SME led to determination of what objectives, or in this case specifications, were important for the durability of fiber-optic cable during installation, it was of critical importance to also determine how much value each specification carries. Since no scale naturally exists for the various fiber-optic cable specifications, they were constructed for this study. A constructed scale is one that is developed for a particular decision problem to measure the degree of attainment of an objective (Kirkwood 1997).

Creating value functions for each specification guides the way to solve this problem towards value-focused thinking as described by Keeney. In this approach the aim was to identify the decision opportunities or, in other words, problem finding. This is a proactive approach to solving the fiber-optic cable problem instead of a reactive approach that is embodied when one uses alternative-focused thinking. An important difference is that in alternative-focused thinking, alternatives are identified before specifying values. Instead, values are specified by establishing a MOE for each cable type before considering alternatives.

As mentioned previously the three specifications used for fiber-optic cable were tensile strength (N), minimum bend diameter (in), and crush (N). An example is shown in Table 1 below.

	Cable Specification					
Manufacturer	**Tensile Strength (N)**	**Min. Bend Diameter**	**Crush**	**TBD**	**TBD**	**Cost**
General-A	2700	3.52	2000	-	-	$16
Draka-B	2775	3.56	2000	-	-	$17
High-High (Made Up)-C	5000	1.8	3000	-	-	$24
High-Low (Made Up)-D	3500	2.52	2000	-	-	$20
TBD				-	-	
MILSPEC Req.	2700	N/A	2000	-	-	-
Gold Standard	5400	N/A	4000	-	-	-

Table 1. Cable Specifications

The four types of cable evaluated are listed under the manufacturer column. The last two rows outline each specification's MILSPEC requirement and a “gold standard” as determined by the subject matter expert. The “gold standard” gives the level of each specification that would be ideal. Of the three specifications listed, both tensile strength and crush had gold standards that were double the military specification. The third specification, minimum bend diameter is a function of the fiber-optic cable’s diameter. For this specification the MIL-PRF-85045F called for a minimum bend diameter as eight times the cable diameter during installation. Again this number was doubled for the gold standard. Since cable companies do not test to the gold standard, these values are not readily available. Instead they test to the MILSPEC values. It is important to note that the gold standards are only estimates because the manufactures have never developed or tested their fiber-optic cables to those limits. The gold standards were created based on the experience and opinion of a fiber-optic cable engineer.

A value function was created for each specification. A value function allows the decision maker to indicate how much value he/she places on the score achieved for a given characteristic. It is created using a zero to one scale, with zero indicating no value and 1 indicating the highest value possible (that is, any score higher than that this maximum measure would not receive any higher value, in this case the gold standard). These values will then be combined with the relative importance of the three characteristics to generate a particular cable brand’s MOE. For simplicity, a linear value function was utilized. This was relatively straightforward for the tensile strength and crush specifications but was more complicated with the minimum bend diameter specification. For tensile strength, a cable meeting the MILSPEC requirement was

assigned a value of 0.5 and a cable meeting the gold standard a value of 1. The SME felt that a cable that met the MILSPEC would be worthy of half the possible value, and this assumption was made for the other two specifications as well. To calculate the values between 0.5 and 1 the slope and y-intercept of the line were determined. The same formulas were used to calculate the value function for the crush specification. In both the tensile strength and crush specifications, the y-intercept was zero because the gold standard was double the MILSPEC requirement.

$$y_2 = 1$$
$$y_1 = .5$$
$$x_2 = GOLDSTANDARD$$
$$x_1 = MILSPEC$$
$$m = (y_2 - y_1) / (x_2 - x_1)$$
$$y = mx + b$$

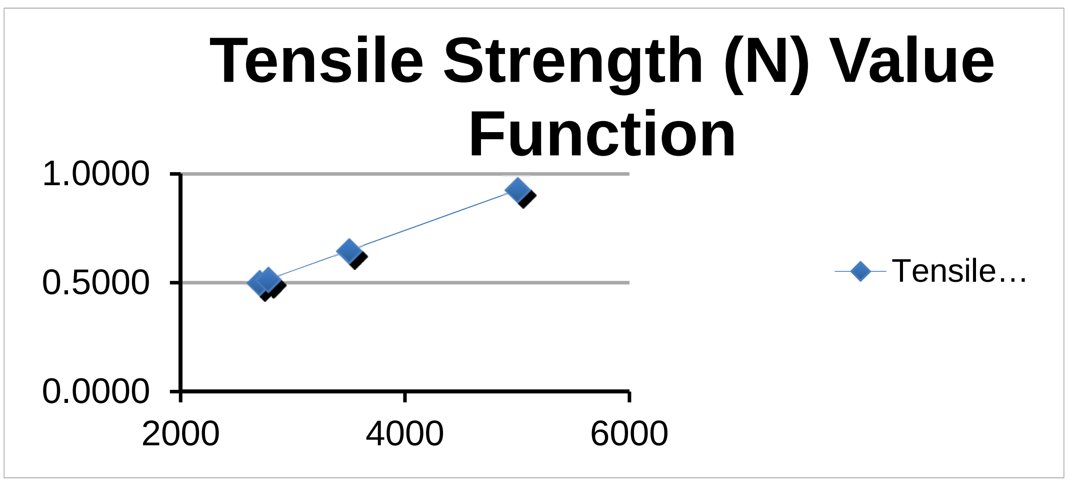


Figure 1. Tensile Strength Specification Value Function

The value function created for the specification for minimum bend diameter was slightly more complicated than the other two specifications because a new slope and y-intercept was required to be created for each cable. This is because the minimum bend diameter is a function of the cable's actual diameter. Again, a cable meeting the baseline MILSPEC requirement of eight times the cable diameter received a value of 0.5 and a cable that met the gold standard requirement of sixteen times the cable diameter received

a value of 1. Thus the same equations were used as outlined directly above, but each cable had its own particular minimum bend diameter that was required by the MILSPEC and by the gold standard. Thus the value function had to be derived four times, once for each cable type. This is demonstrated in Table 2. In Table 3 one can see the final values received by each cable types' specification.

Min. Bend Diameter			
	Specification	***Value***	
Cable A	3.52	0.5	
Cable B	3.56	0.5	
Cable C	1.8	1	
Cable D	2.52	0.75	
MILSPEC Req.	A	3.52	0.5
	B	3.56	
	C	3.6	
	D	3.36	
Gold Standard	A	1.76	1
	B	1.78	
	C	1.8	
	D	1.68	
Slope-A	-0.284090909		
Y-Intercept-A	1.5		
Slope-B	-0.280898876		
Y-Intercept-B	1.5		
Slope-C	-0.277777778		
Y-Intercept-C	1.5		
Slope-D	-0.297619048		
Y-Intercept-D	1.5		

Table 2. Minimum Bend Diameter Value Function Calculations

	Cable Specification		
Manufacturer	Tensile Strength (N)	Min. Bend Diameter	Crush
A	0.5	0.5	0.37037037
B	0.513888889	0.5	0.37037037
C	0.925925926	1	0.740740741
D	0.648148148	0.75	0.555555556

Table 3. Cable Specification Values

3. Relative Weighting

The next part of the MOE model is the relative importance weights. Each characteristic is assigned a relative weight based on how important it is for installation performance. The cable engineer helped develop the relative importance of the three specifications. This was an important step because it would provide the final quantification of the MOEs, which would then be used extensively in both probabilistic and simulation models. Discussions with the cable engineer led to the weights shown in Table 4.

Specification	Weight
Tensile Strength	40%
Minimum Bend Diameter	40%
Crush	20%

Table 4. Relative Weights for Each Cable Specification

4. Measure of Effectiveness

Next the MOE for each manufacturer's cable is calculated. For example, Cable A's tensile strength had a value of 0.5. This value would be multiplied by the weight for tensile strength (40%) to achieve a weighted value of 0.2. This same procedure would be performed for minimum bend diameter and crush. After the three weighted values were determined for a cable they were summed to provide the MOE as shown in Table 5.

	Weighted Values			MOE
Manufacturer	Tensile Strength	Min. Bend Diameter	Crush	Sum
A	0.2000	0.2000	0.0741	**47.4074%**
B	0.2056	0.2000	0.0741	**47.9630%**
C	0.3704	0.4000	0.1481	**91.8519%**
D	0.2593	0.3000	0.1111	**67.0370%**

Table 5. Cable Specification Weighted Values with Final MOEs

5. Geometric Distribution

The geometric distribution was used to model the number of times the cable would have to be re-run. For any given cable there is uncertainty as to how many installations will be required before it is successfully installed. The geometric probability distribution provides the appropriate analytical model for this type of event. The first step is to determine a rework percentage or probability of failure. A linear function of the MOE was used:

$$\text{Rework \% (Probability)} = 1 - \mathit{MOE}$$

This assigns a lower probability of rework to cables that have higher MOEs. The geometric distribution is appropriate for optical cable installation because once a cable has been successfully run it is left in place. Effectively this is to search for the first success, and the geometric distribution gives the probability distribution of the number of Bernoulli trials until the first success (Hayter 2006).

$$\Pr(X = n) = (1 - p)^{n-1} p$$
$$\text{for } n = 1,2,3,...$$

Equation 1. Geometric Distribution

In this instance *p* is the MOE and *n* is the number of reworking runs until a fiber-optic cable has been successfully laid. Table 6 below shows for the four types of cables used in the model's example and the probabilities for each occurrence.

Geometric Distribution				
No. of Reworking Runs Until Success	***A***	***B***	***C***	***D***
1	47.41%	47.96%	91.85%	67.04%
2	24.93%	24.96%	7.48%	22.10%
3	13.11%	12.99%	0.61%	7.28%
4	6.90%	6.76%	0.05%	2.40%
5	3.63%	3.52%	0.00%	0.79%
6	1.91%	1.83%	0.00%	0.26%
7	1.00%	0.95%	0.00%	0.09%
8	0.53%	0.50%	0.00%	0.03%
9	0.28%	0.26%	0.00%	0.01%
10	0.15%	0.13%	0.00%	0.00%
11	0.08%	0.07%	0.00%	0.00%
12	0.04%	0.04%	0.00%	0.00%
13	0.02%	0.02%	0.00%	0.00%
14	0.01%	0.01%	0.00%	0.00%
15	0.01%	0.01%	0.00%	0.00%
16	0.00%	0.00%	0.00%	0.00%
17	0.00%	0.00%	0.00%	0.00%
18	0.00%	0.00%	0.00%	0.00%
19	0.00%	0.00%	0.00%	0.00%
20	0.00%	0.00%	0.00%	0.00%

Table 6. Geometric Distribution Results

Table 6 shows that for cables A and B it would take no more than six runs to achieve a 99% probability of a successful run, no more than two runs for cable C, and no more than three runs for cable D. This was important to note for each cable because it helps to define the trade space when beginning to incorporate the cost per foot of cable. The length of the cable run was not accounted for to alter the probability of successfully running the cable since the rework probability was based entirely on the cable construction, which is uniform throughout regardless of length. A cable’s construction does not change if the cable is five feet in length or one thousand feet in length. The same materials, specifications, and standards are adhered to for the cable regardless of length. While the potential exists for a longer cable to experience more issues during installation, the initial model here did not consider the effect of cable run length and breakage and rework.

6. Measuring Cost

The next step was to calculate the expected frequency, or number of runs expected, for a particular cable. For a geometric distribution the expected value is given as:

Frequency(Number of Runs):

$$E(x) = 1/p$$

where p is the MOE

Equation 2 – Expected Number of Runs

The expected cost for a specific cable is then calculated as:

Expected Cost per Cable:

$$E(x) = (1/p) * cable\ length(ft) * \text{cost per ft}$$

Equation 3 - Expected Cost per Cable

The total cost based on the number of runs required to achieve a 99% probability of success was also calculated. Six runs for cables A and B, two runs for cable C, and three runs for cable D. This represents the amount that would have to be budgeted for cable material so that there would only be a 1% chance of a cost overrun. These costs were calculated by multiplying the run number by the cost of one run of a given length and are shown in the Table 7.

Total Cost for 99% Probability of Successful Completion								
Manufacturer	1	2	3	4	5	6	7	8
A	$ 16,000	$ 32,000	$ 48,000	$ 64,000	$ 80,000	$ 96,000	$ 96,000	$ 96,000
B	$ 17,000	$ 34,000	$ 51,000	$ 68,000	$ 85,000	$ 102,000	$ 102,000	$ 102,000
C	$ 24,000	$ 48,000	$ 48,000	$ 48,000	$ 48,000	$ 48,000	$ 48,000	$ 48,000
D	$ 20,000	$ 40,000	$ 60,000	$ 60,000	$ 60,000	$ 60,000	$ 60,000	$ 60,000

Table 7. Total Cost for 99% Probability of Successful Completion

The costs from Table7 are graphed on a bar chart in Figure 2 to illustrate how the relative total cost per cable can change depending on the number of runs. Note that once there is a 99% probability of success, there is no additional cost, since it is extremely unlikely that more runs will be required, and therefore no additional cost will be incurred.

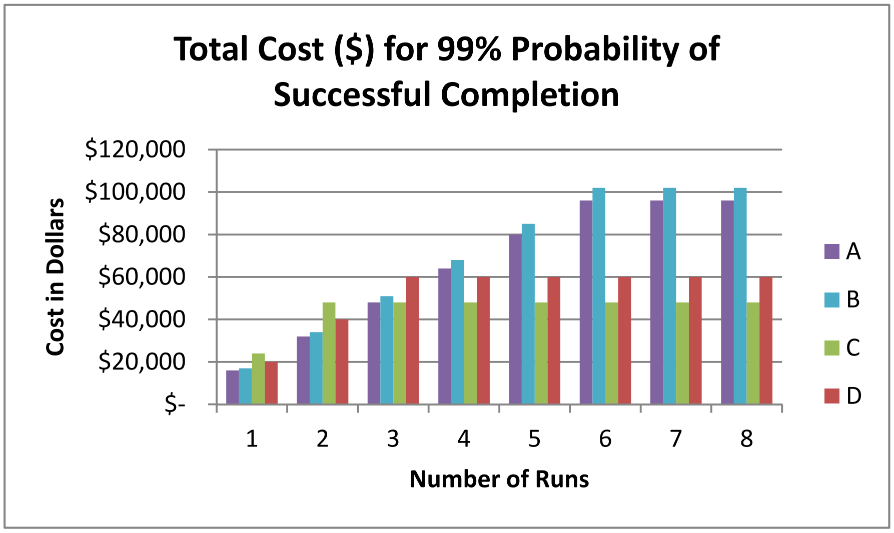


Figure 2.   Total Cost for 99% Probability of Successful Completion

Figure 2 shows the relative cost effectiveness of each cable type depending on the number of runs required. For example, if only one or two runs are required, then cable A is the least cost option. However if three or more runs are required, then cable C is least cost option.

It is important to delineate between different types of cost. In this case the cost per foot is higher for a cable with a stronger MOE, but the total cost over time would lower because the probability of rerunning the cable is far less for the high MOE cable. This is especially true for large projects where hundreds of thousands of feet of cable are being run. While this research did not include the length of run as a factor, exploring the effects and impacts of the cable run length would be valuable for future research.

C. SIMULATION MODELING

A three-step approach was utilized for the analysis. The first step was to use characteristics of fiber-optic cables to develop a measure of effectiveness (MOE) for

installation quality. The MOE model was applied to specification data from different manufacturer's fiber-optic cable. The individual fiber-optic cable manufacturer MOE's provided a basis to evaluate the expected level of rework for each cable. The second step was to use this estimated level of rework in a geometric distribution to estimate the total expected cost of installation for each cable type. The third step was to use a simulation model with the number of reruns modeled using a geometric distribution and the amount of time required for each run using a Beta distribution. The simulation model was used to explore the cost and schedule risk associated with each of the cable alternatives.

The software package chosen to perform the simulation analysis was "Imagine That!" Incorporated's ExtendSim Suite 8.0.1. This software suite utilizes a graphical user interface (GUI). GUI (pronounced goo-ey) is a type of programming interface that allows the user to interact with graphical icons in lieu of writing out all the commands in text. The vast majority of the programming commands in ExtendSim are handled with the user connecting the graphical icons, and the remainder coding is done by writing text commands inside of certain graphical icons. The end product of the ExtendSim simulation code is a pictorial representation of the entire model with only a small amount of the coding hidden inside the graphical icons that comprise the model.

1. Number of Runs

The first step in the simulation modeling was to set up the model in ExtendSim and validate the model based on the analytical values calculated for the geometric distribution. Initially time was held constant at twelve hours (the average amount of time our SME said it would take to run 1,000 feet of cable). Since the simulation counted in intervals of 12, each run result was divided by 12 to get the number of runs. These numbers were then summed to calculate the frequency of the cable runs. The model built for the thesis research was far more extensive than was needed for this research. We will highlight the aspects of the model that are relevant to the thesis. The additional aspects of the simulation model, not covered here, will be broken down later for utilization in future thesis research. The ExtendSim model provided a series of 1000 individual discrete event simulations of fiber-optic cable being run by a shipyard.

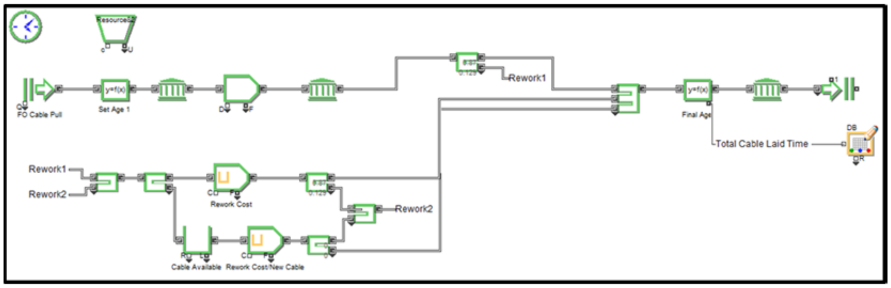


Figure 3. Baseline ExtendSim Model

Each individual simulation began in a Create block where ExtendSim created the item using a constant distribution. When the item was created an individual attribute "birthtime" was assigned to that item. This "birthtime" was then used to track the age of the item as it moved through the simulation. The age of the item was set by a simple line of code inside of an Equation block which specified that "age" be equal to "currenttime" minus "birthtime." The handle "currenttime" is a term recognized by ExtendSim to mean the time currently seen at a single instant in time during the simulation. Assigning the attribute "birthtime" inside the Create block allowed the tracking of an attribute age at the end of the simulation.

Once the item age was assigned, it proceeded to an Activity block. In the Activity block the item was delayed for a time step of "n" hours to simulate a length of cable being run. The item time step inside this block can be easily modified to specify any length of time. For our purposes we assigned a value of 1 hour to make tracking easier at the end of the simulation.

Once the item exits the Activity block it travels to the first Select Item Out block. Here at the Select Item Out block the item has an option to continue on one of two paths based on its MOE. The item can either exit the block having successfully installed the cable or it can proceed to the first "rework" loop. The chance that the item exits the block successfully is directly proportional to MOE and is modeled using a geometric distribution that provides the first success after "n" number of failures.

If the item goes to the "rework" loop it will enter another Activity block. Inside this Activity block a time step of "n" hours is once again assigned. For ease of tracking a

value of 1 hour was assigned inside each of the remaining Activity blocks until the fiber-optic cable installation is successfully completed in a simulated run.

After exiting the Activity block in the rework loop the item enters another Select Item Out block. This block is based on the MOE for a successful installation of the fiber-optic cable by the simulated shipyard installation team. This block, and all future Select Item Out blocks, works exactly the same as the original Select Item Out block described for this simulation. The item has the same option as in the original Select Item Out block. It can either proceed to the finish or it can proceed to another rework loop.

The item will either proceed towards exiting the simulation or continue to proceed to a rework loop until the simulation time clock reaches 200 hours where it will be forced to exit the simulation. The choice of 200 hours was based on geometric distribution results and not one the 4000 individual discrete event simulations for this thesis progressed that far.

Whenever the item successfully exits the Select Item Out block it goes through a Select Item In block. The point of the Select Item In block is to merge all of the simulated loops in the simulation. This block serves no other purpose nor does it add any time to the simulation.

After exiting the Select Item In block the item passes through another Equation block. This particular Equation block is a check to ensure that the items age has been successfully calculated. It serves primarily as a back-up to the original Equation block to ensure that each individual runs data is captured. The data calculated in this Equation block is sent directly to a Write block.

The Write block saves each of the individual runs data for analysis at the completion of each 1000 run simulation. The Write block re-writes itself after every simulation in ExtendSim, requiring the export of all data for this block to an Excel workbook sheet for further analysis.

The final destination for each individual item in the simulation is the Exit block. Once an item reaches an Exit block ExtendSim knows that that individual discrete event simulation has been completed. Once the item completes an individual simulation run

ExtendSim can start the next run. The simulation will continue in this manner until all 1000 runs have taken place. If an item manages to get stuck in the simulation at any time an arbitrarily time was chosen to end an individual simulation. The arbitrary time selected was 200 hours. If a value of 200 hours was detected in the Excel workbook sheet it was to be discarded as an outlier. Not one of the 4000 runs analyzed had a value of 200 hours. This meant that no item was ever trapped in the simulation and that every item successfully made it to the Exit block.

2. Time and Labor Cost

In order to incorporate labor costs into the simulation, two additions had to be made to the previous model. These two changes were the incorporation of a "set block" and a "get block". Inside of the "set block" an attribute "_cost" was created which allowed the model to track costs throughout each of the activity blocks. Before the data exited the simulation it passed through the "get block". This block calculated the total cost incurred for each run throughout all of the simulations. A picture from ExtendSim displaying this updated model is below.

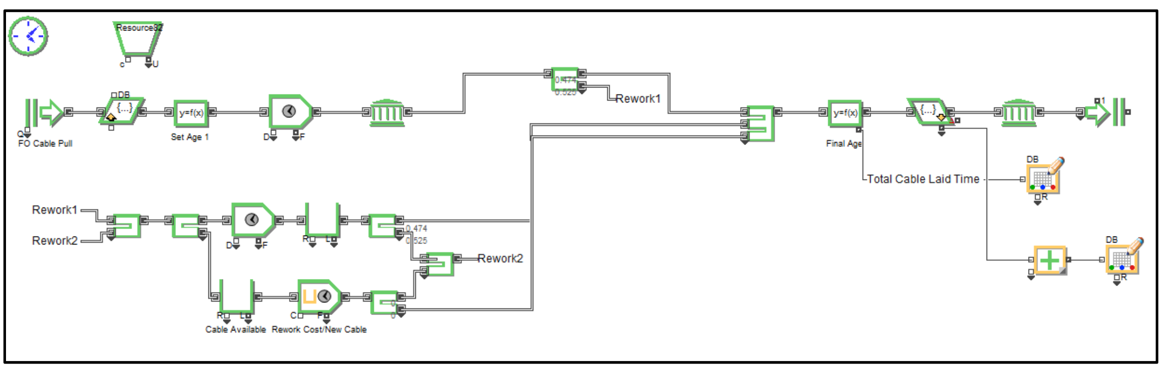


Figure 4. ExtendSim Screenshot

The first part of the simulation looked only at the material costs associated with running and reworking fiber-optic cable. While this can provide a good indicator as to which cable may be the best to purchase it is incomplete because it does not incorporate the hourly labor costs associated with running a cable. In this section these additional labor costs were incorporated while simulating the run of a 1,000 foot long fiber-optic

cable. This assumed that the run would be lower bounded by a time of 12 hours to complete, and it would require six cable workers at a rate of $15/hour each to complete. Because the actual cable run time was uncertain it was assumed that the cable run time would be similar in form to that of a beta distribution. A beta distribution is a distribution of random proportion such as the time to complete a task. In this beta distribution, the maximum run time was 24 hours, the minimum run time was 12 hours, alpha was 1.5 hours and beta was 3 hours.

The conclusions section of this thesis (Chapter VI) will outline how the model can be used to track existing cable in the shipyards supply, track the cost to run the cable, and how the probability of fixing a cable than continuing to rework/rerun it can be used.

THIS PAGE INTENTIONALLY LEFT BLANK

V. ANALYSIS

A. ANALYTICAL RESULTS

1. Expected Cost

Based on the geometric distribution, cable C has the lowest expected number of runs (frequency) and the lowest expected cost as outlined in tables *7* and *8* below. This particular cable had the highest MOE (92%) and consequently the lowest percentage for rework (8%). Cable C has the largest upfront purchase cost (cost per foot) and is the most expensive of the four cables in question which upon first glance may appear to be less appealing.

Cable Type	Expected Number of Runs (Frequency)
A	2.11
B	2.08
C	1.09
D	1.49

Table 8. Probabilistic Model Expected Number of Runs Per Cable

Cable Type	Expected Cost
A	$ 33,750
B	$ 35,444
C	$ 26,129
D	$ 29,834

Table 9. Probabilistic Model Expected Cost Per Cable

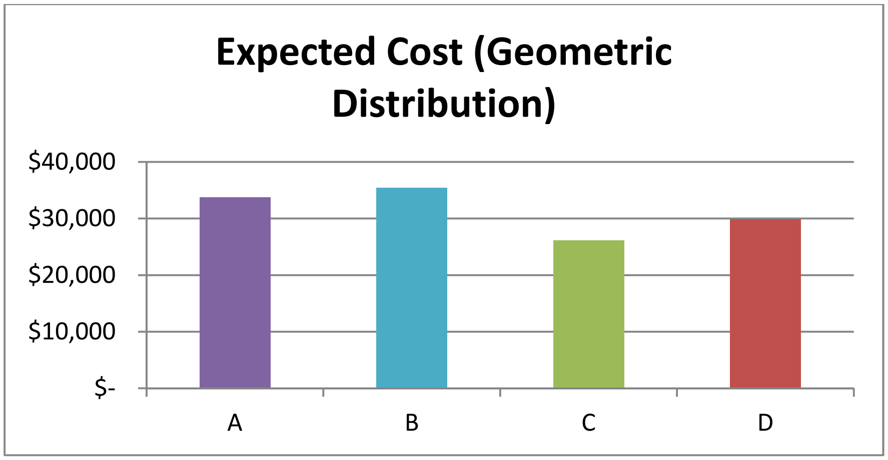


Figure 5. Expected Cost, Probabilistic Model

Despite the fact that cable C is the most expensive per foot, based on the total cost to achieve a 99% probability of success (as shown in Table 7), the analysis indicates that cable C is the lowest cost solution for three runs or more. This is true because there is only a 1% chance that cable C will have to be rerun more than two times, while there is at least a 25% chance that the cheaper (per foot) cables A and B will have to be rerun more than two times.

While the analysis was based on material cost, clearly the savings will be realized in both cost and schedule terms, especially as the number of cable runs required for successful installation increases.

B. SIMULATION RESULTS

1. Expected Cost

Initially the simulation model was validated by comparing the simulation results to the expected values of the geometric distribution shown in Table 6 and the frequencies shown in Table 10. The simulation was run four separate times for each cable type. Each simulation consisted of 1,000 trials. In the simulation the individual cable's MOE was used as a probability. For example, an MOE of 60% would indicate there is a 60% chance of running the cable successfully and a 40% chance of the cable requiring rework. After 1,000 runs with each cable type the results were as follows:

Cable A		**Cable B**		**Cable C**		**Cable D**	
Run	*Frequency*	*Run*	*Frequency*	*Run*	*Frequency*	*Run*	*Frequency*
1	472	1	495	1	919	1	670
2	259	2	233	2	75	2	214
3	137	3	134	3	5	3	81
4	63	4	63	4	1	4	20
5	33	5	37	5	0	5	11
6	17	6	17	6	0	6	3
7	7	7	6	7	0	7	0
8	2	8	10	8	0	8	1
9	7	9	3	9	0	9	0
10	2	10	1	10	0	10	0
11	0	11	1			Sum	1000
12	0	12	0	Sum	1000		
13	1						
		Sum	1000				
Sum	1000						

Table 10. Simulation Results (Frequency Only)

These results are almost exactly identical to the results of the geometric distribution in Table 7. After each cable was simulated 1,000 times the average number of to the frequencies calculated using the geometric distribution. The expected numbers of runs (shown in Table 11) are also nearly identical to the values calculated for the geometric distribution.

Cable Type	**Expected Number of Runs (Frequency)**
A	2.08
B	2.07
C	1.09
D	1.50

Table 11. Simulation Expected Number of Runs Per Cable Type

Next the expected cost was calculated by multiplying the expected number of runs for each cable from the simulation by the cost of a 1,000 foot long run of cable. The results for these calculations are found in Table 12.

Cable Type	Expected Cost
A	$ 33,296
B	$ 35,224
C	$ 26,112
D	$ 30,040

Table 12. Simulation Expected Cost Per Cable

The expected cost values provided by the simulation are nearly identical to the values provided by the geometric distribution in the probabilistic model (see Table 9). The fact that the frequency and expected cost values of the simulation model match the probabilistic model verifies that the simulation model is correct. This will be useful later when incorporating time variants because they cannot be easily modeled probabilistically and the simulation model is the only tool available.

2. Time and Labor Cost

The simulation results in the section above confirmed the results of the probabilistic model and geometric distribution. This also validates the simulation and allows the model to be used for further analysis and future work. The cost to install cable is not solely based on material costs. Time, and consequently labor, cannot be ignored when discussing cable installation costs. In order to incorporate time and labor a beta distribution was inserted into the ExtendSim model. The distribution's location was twelve hours, the maximum value was twenty-four hours, the value for a was one and half hours, and the value for b was three hours. The location value is the distribution's lower bound. The intent was to devise a distribution with an average cable run time of twelve hours; however, it became the lower bound instead (i.e., no cable could be run in less than 12hours).

A beta distribution with parameters a > 0 and b > 0 has a probability density function:

$$f(x) = \frac{\Gamma(a+b)}{\Gamma(a)\Gamma(b)} x^{a-1}(1-x)^{b-1}$$

Equation 1 - Beta Distribution Definition

These values allowed for a lower bound around twelve hours which was the average time to run a 1,000 foot long fiber-optic cable onboard a recent new construction naval vessel (Anonymous Person A 2012).

	Cable A		Cable B		Cable C		Cable D	
	Hours	Cost	Hours	Cost	Hours	Cost	Hours	Cost
Average	44.58533	$39,853	40.2271	$38,810	21.0801	$27,817	28.3167	$29,748
Max	191.8543	$161,267	142.3000	$131,807	72.5126	$78,526	91.7150	$88,254
Min	12.29833	$17,107	12.4373	$18,119	12.3557	$25,112	12.5321	$21,128

Table 13. Beta Distribution Results

The simulation was run four separate times for each cable type. Each simulation consisted of 100 trials. In the simulation the individual cable's MOE was used to determine the probability of rework. The beta distribution assigned time uncertainty to each cable run. Table 13 shows the results for 100 runs with each cable type. All cables included a labor rate of $90/hour for a six-man team with each member earning $15/hour. For example, cable A took 44.58 hours on average to be successfully run over the course of 100 runs. The multiple material costs, as well as the hours required to complete the installation sum to an average cost of $39,853. The maximum and minimum simulation results were included as well. Figure 6 below is a visual representation of the average or expected cost.

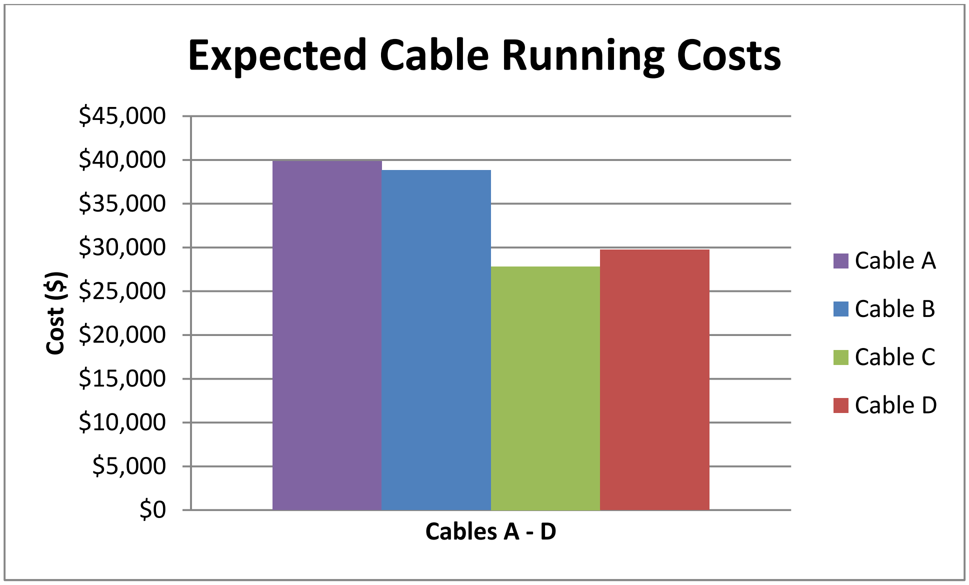


Figure 6. Expected Cost of cable Installation Including Materials and Labor

Even incorporating time and labor with the beta distribution still resulted in cable C being, on average, the best choice. These results mirrored the results from the probabilistic model that did not include time and labor costs. However, the minimum values provided by the beta distribution showed that if a less expensive cable can be run in only twelve hours it will be substantially cheaper than the more expensive cable types. The question then becomes at which point is it too risky to purchase the cheaper cable.

3. Cost Risk

An interesting way to examine the results of our analysis is to consider the cost risk implications. Begin by looking at the material costs only. Recall that the geometric distribution provided the likelihood of a successful installation after a given number of runs as shown in Table 9. Suppose it is needed to install 1,000 feet of cable and there is a budget of $51,000 for cable material. If that budget was used to buy cable C, there will be enough for two runs and the chance of a cost overrun will be 1%, because there is a 99% probability that cable C will be successfully installed in two runs or less. If the same budget is used to purchase cable A or B, there will be enough cable for three runs, but there will be a 12% chance that it will require four or more runs to successfully install the cable, which may lead to a cost overrun of at least 33% or more (based on the original budget).

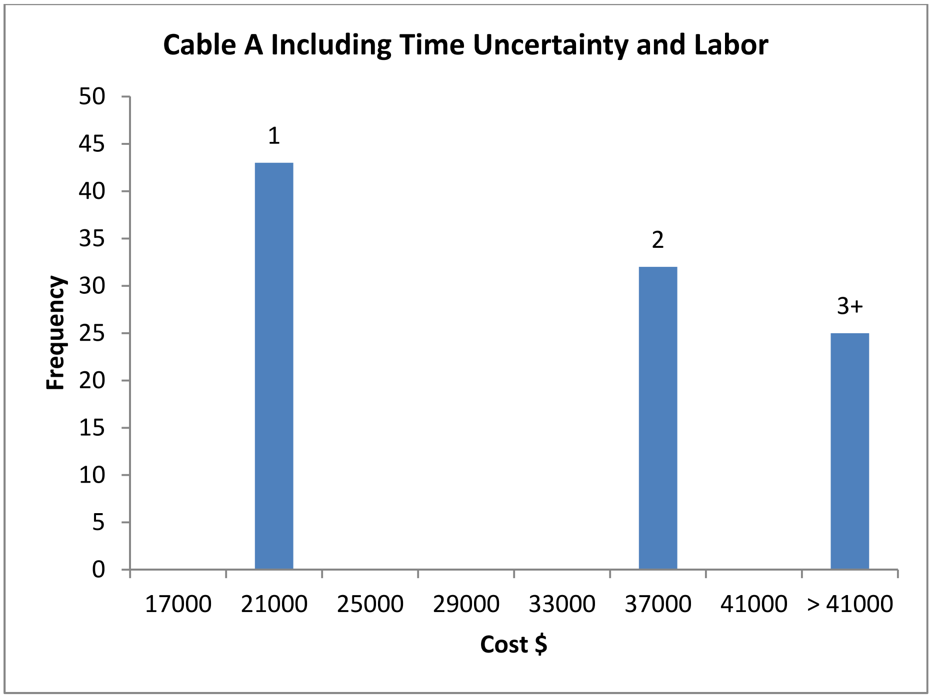


Figure 7. Simulation Histogram (Cable A) Including Time Uncertainty, Labor, and Material Cost. Values Above Each Bar Indicate the Number of Runs Required for a Successful Installation.

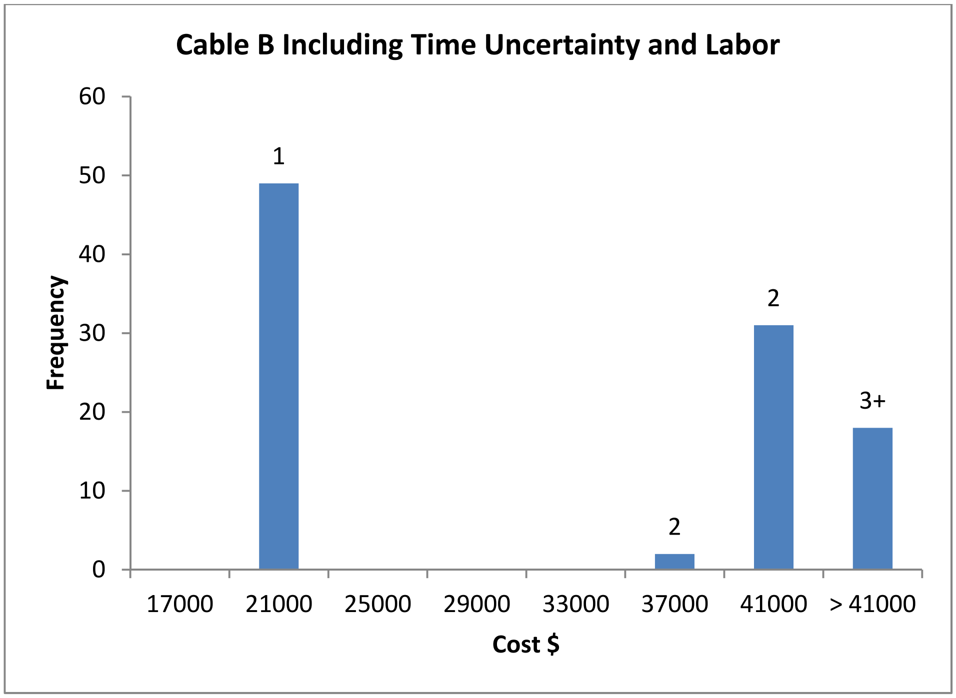


Figure 8. Simulation Histogram (Cable B) Including Time Uncertainty, Labor, and Material Cost. Values Above Each Bar Indicate the Number of Runs Required for a Successful Installation.

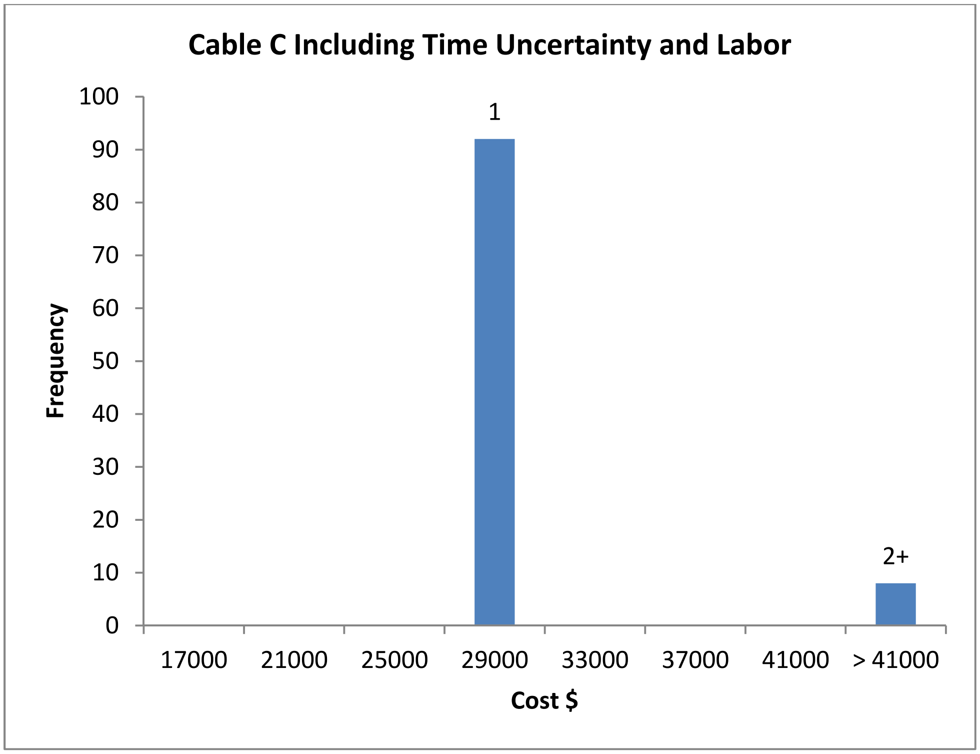


Figure 9. Simulation Histogram (Cable C) Including Time Uncertainty, Labor, and Material Cost. Values Above Each Bar Indicate the Number of Runs Required for a Successful Installation.

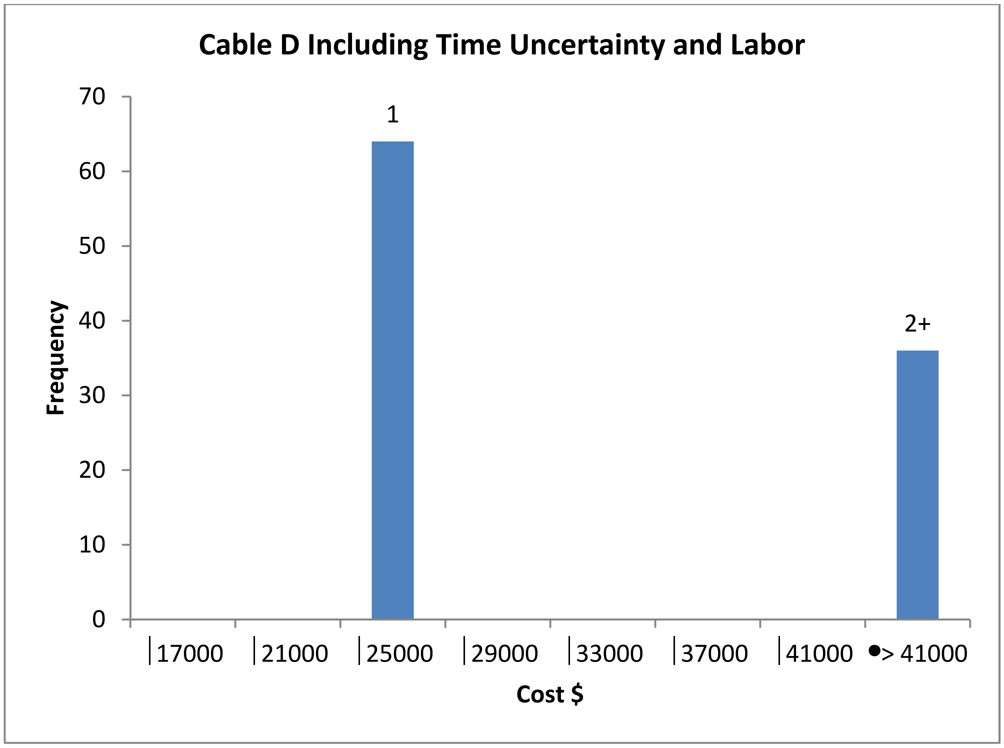


Figure 10. Simulation Histogram (Cable D) Including Time Uncertainty, Labor, and Material Cost. Values Above Each Bar Indicate the Number of Runs Required for a Successful Installation.

Based on the results of the second simulation (Figures 7 through 10), which includes time uncertainty and labor costs as well as material costs, it is possible to make a similar analysis. The bins label found in these histograms represents a dollar value range. For example the 21,000 bin includes all simulation runs between 17,000 and 21,000 in dollars. Suppose there is a budget of $41,000 for installation including labor and materials. The risk of going over this budget with cable A is 25%, with cable B is 18%, with cable C is 8%, and with cable D is 36%. Clearly cable C has the lowest cost risk. In fact, it is possible to reduce the budget to $30,000 and still not increase the risk with cables C and D, while the cost risk for that budget would increase significantly for cables A (57%) and cable B (52%). Even when time uncertainty and labor costs are factored in cable C remains the best choice. However, if a shipyard could only choose between cables A, B, and D because of cable availability or contracting issues, it would make the most sense to choose cable B. This cable has a slightly lower risk of incurring a cost

overrun (18%) compared to the other two cables. Cable B being the preferred choice over cable D appears counterintuitive because of its lower MOE. These results stem from the prevailing labor rate and the material cost of the cable. In order to further explore this trade space a sensitivity analysis will be performed comparing cables B and D when labor rates and cable costs are altered.

4. Sensitivity Analysis

Once the cost risk associated with purchasing a specific fiber-optic cable was established using the simulation model, a sensitivity analysis was conducted to examine the effect of input values on cost. A sensitivity analysis determines the uncertainty associated with an output of a mathematical model (for this thesis the output is cost) through the adjustment of a single input while holding all other existing inputs constant. Two inputs were investigated, labor cost and cable purchase price, in order to see to what extent the varying of these inputs would affect the results determined in the cost risk section.

Varying the purchase cost of cables did not have a significant impact when compared to the previous results shown in the cost risk section; however, varying the labor cost did have a significant impact for cables B and D when compared to the previous results shown in the cost risk section. A second simulation was run two times, with 100 trials each, for each cable with labor costs at \$90/hour and \$200/hour respectively. Cable B posed less overall risk for going over budget in the simulation model when compared to cable D. The percent of cost risk for going over budget (\$41,000) with cable B in the simulation was 27%. The percent of cost risk for going over budget with cable D in the simulation model was 31%. When the cost of labor was raised from \$90/hour for a crew to run fiber-optic cable to \$200/hour for a crew to run cable, the higher resultant risk for cables B and D switched. In the higher labor cost model cable B had a percent risk of over run of 38% compared to cable D which now had a 37% risk of over run. The results are shown in Figure 11 and Figure 12:

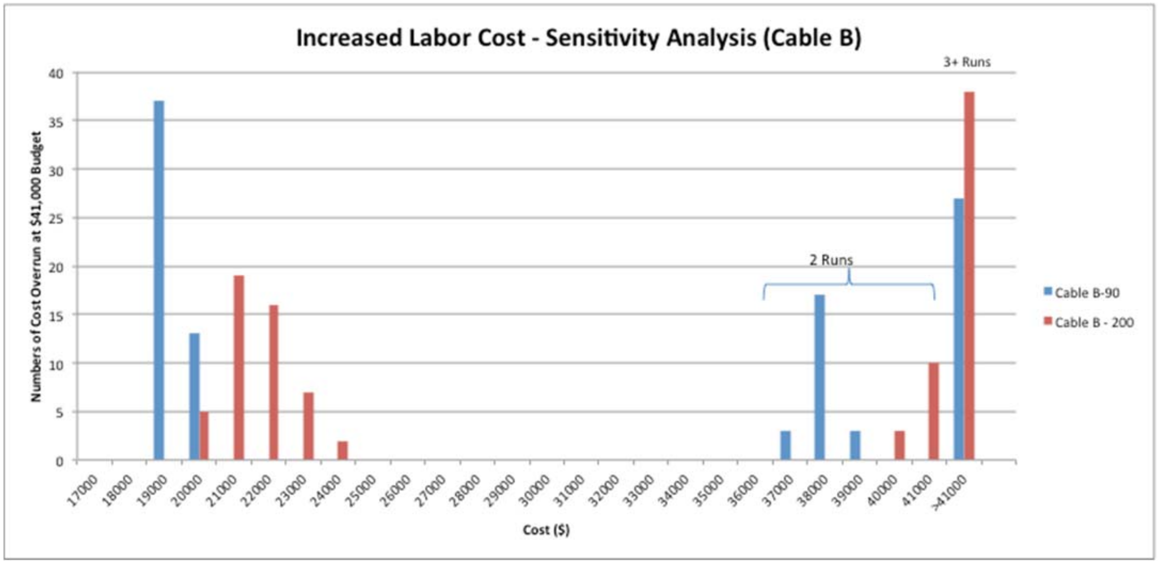


Figure 11. Increased Labor Cost - Sensitivity Analysis (Cable B)

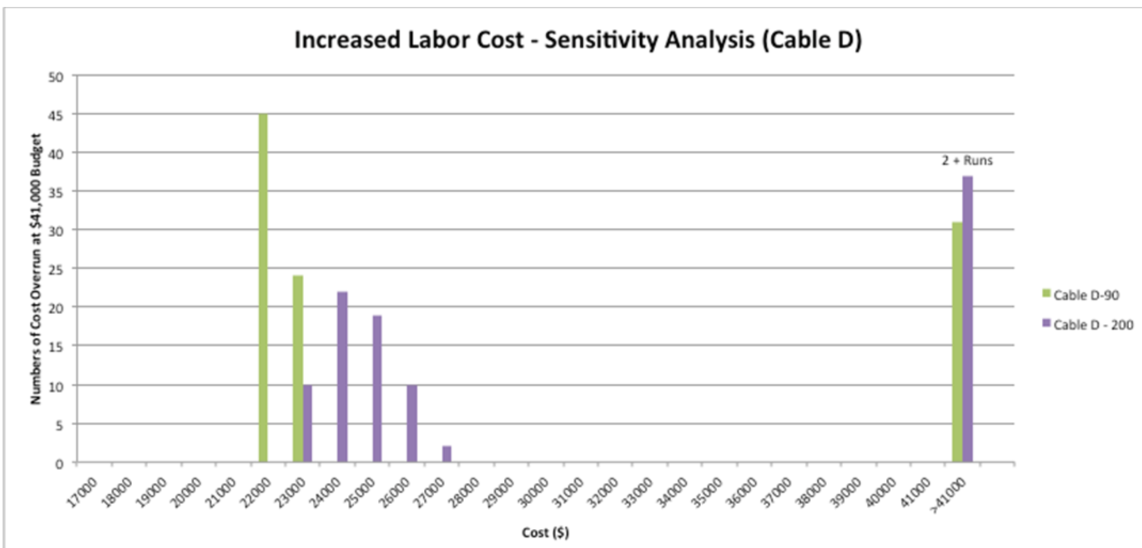


Figure 12. Increased Labor Cost - Sensitivity Analysis (Cable D)

It was important to note that at the higher labor rate, both cables probability of overrun increased slightly. However, since the overrun probabilities for cables B and D (38% and 37%) were quite close and possibly due to random uncertainty, another simulation was run with 600 trials at the higher labor rate. During this simulation cable B had an overrun chance of 29% and cable D had an overrun rate of 33%. This is

interesting because it points again, even at a higher labor rate, that a lower MOE cable (B) is a more sound option in terms of cost risk.

A basic analysis of the 600 trial simulation shows that cable B required on average two cable runs for successful installation and cable D required an average of 1.5 runs. This provides an expected material cost for each cable at $32,000 and $30,000 respectively. Since labor rates are constant, the expected value of the cables will move up or down based on the rate, but cable B will always have the higher expected value. The average of 600 runs left an average installation value for cable B of $39,244 and for cable D this value was $35,544.

When a budget is put in place it can affect the selection of the cable. For example, with a $41,000 budget the $90/hour labor rate is a low enough value to absorb the labor costs on the rare occasion when a second run of cable D has to be run. This reserve being found in the material price difference between the two cables. Conversely, the $200/hour labor rate causes this reserve to be consumed much more rapidly and will result in the cheaper cable having the lower risk of cost overrun. It is important to note however that when no budget is in place the expected cost for installing the lower quality cable is still higher.

5. Summary

After including time uncertainty and labor costs into the simulation models, the results suggest that the cable with the highest MOE, cable C is the best choice. These results are dependent on cable material cost and labor rates as shown by the sensitivity analysis. The simulation model developed for this thesis is a very adaptable model that can be used for future research in a variety of ways. These future areas of research will be discussed in the next chapter.

THIS PAGE INTENTIONALLY LEFT BLANK

VI. CONCLUSION

A. SUMMARY

This thesis developed a cost-optimization model for fiber-optic cable installation in naval shipyards. One aspect of cable laying that proved troublesome and a good candidate for developing optimization models was fiber-optic cable installation. The installation of fiber-optic cable is a difficult and delicate process that often results in multiple attempts to run a length of cable. This served as a starting point for developing an optimization model that would help specify which specific fiber-optic cable should be used for installation in order to minimize rework.

Following the shipyard visits and discussions with various cable and shipyard subject matter experts, the thesis refined to three questions:

- Is the total cost of installation less for running higher quality fiber-optic cable over a baseline MILSPEC version?
- Are the cost savings great enough to specify a higher quality cable?
- What's the relative cost risk presented by cable types?

In most cases the total cost of installing a higher quality fiber-optic was less than total cost of installing a baseline MILSPEC version cable. When a budget is not set on a particular cable run (of any length) the cable with the highest MOE will always result in the lowest expected cost. In the research it was determined the more expensive cable at $24/ft had an MOE around 92% and the baseline MILSPEC cable was $16/ft with an MOE around 47%. Even at a cost of 150% greater than the cheaper cable, there was never an instance of the lower MOE cable having a lower total cost. This was due to the high number of reruns that occur when less effective cable is used.

During analysis of both probabilistic and simulation models the cost savings realized by installing a higher quality fiber-optic cable varied but all were significant. For a 1,000-foot run of fiber-optic cable, the cable with the highest MOE was cheaper by a minimum of approximately $3,000 to a high of approximately $10,000 over the three other cable types. This is a cost savings range between ten and twenty-five percent. The

extra time added to ship construction schedules by choosing a lower MOE cable may make the savings even greater when using a higher quality cable.

Cost risk for a cable type becomes an issue when a budget is set by the shipyard for a particular cable run. The analysis shows that the highest quality cable had the lowest cost risk, but this relationship was not as clear with the lower quality cables. Specifically, a relatively high quality cable (cable D – 67% MOE) may not always perform as a lower quality cable, such as cable B (MOE 47%) when a budget is set. A lower quality cable is less expensive and multiple runs of the cable may be possible before running over budget. Conversely, in the cables above, cable D went over budget after the second cable run because of its higher material cost. The significant cost difference between the cables allowed for a lower quality cable to have a better chance of being run under budget, while the better quality cable had a lower chance of being run under budget. However, it is important to acknowledge that the expected cost for the higher quality cable will still be lower than the expected cost of the lower quality cable

A key contribution of this research is the quantification of the cost risk associated with cable quality. Although the engineers in the shipyards thought that higher quality cable could lead to lower overall costs, they did not have a model to prove it. This thesis provides them with a model that can be used to evaluate cables and quantify the cost risk for any given budget. This should help improve the efficiency of the shipyards.

B. RECOMMENDATIONS AND FUTURE RESEARCH

The analysis and findings of the optimization models developed in this thesis are providing a starting point that could be implemented into future research regarding cable installation. The overall concept and design of the models provided herein, while carefully constructed, are still immature. Refinement of these models will provide greater insights and serve as a more accurate cost predictor tool for shipyards when selecting fiber-optic cable. Recommendations for future areas of research for optimizing fiber-optic cable installation aboard naval vessels are:

- Refined Measure of Effectiveness development, including other cable types such as power cable. Recommend further consultation with fiber-optic cable engineers to improve the MOE function of the probabilistic

model. This will improve the models accuracy. Consultation with engineers for various types of cable will also allow model expansion thus rendering a model that can be used conclusively for all cable types.

- The simulation model has a lot of built in functionality that was not utilized in this thesis. The as-built model has the ability to examine varying labor force (personnel skill level), cable purchasing philosophies (just in time, on-sight, etc.), including time for removing a damaged cable, and repair of cable. All of these areas require consultation with subject matter experts to generate datasets and understand the best method of incorporation. They can be pursued individually or as a whole.
- The final recommendation for future research is to examine when a fiber-optic cable breaks during installation as a function of the cable's MOE. Essentially, it would be valuable to identify at what location and what time the cable is most likely to break. This may impact cable selection and installation practices.

As the next generation of naval vessels become increasingly more dependent on fiber-optic cable to operate and perform, an optimization strategy becomes more important than ever. The optimization analysis and methodology performed in this thesis serve as a good starting point for continuing this research and are vital for the improvement of ship construction in the U.S. Navy and U.S. Coast Guard.

THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX A

There are additional military specifications that cover the optical fiber within the fiber-optic cable (MIL-PRF-49291C), and the military standard for the installation of fiber-optic cable (MIL-STD-2042-1B(SH)). MIL-PRF-49291C governs performance specifications of the optical fibers found within the fiber-optic cable. MIL-STD-2042-1B(SH) provides standardized methods for installing fiber-optic cable onboard surface and subsurface naval vessels regardless of the class of ship.

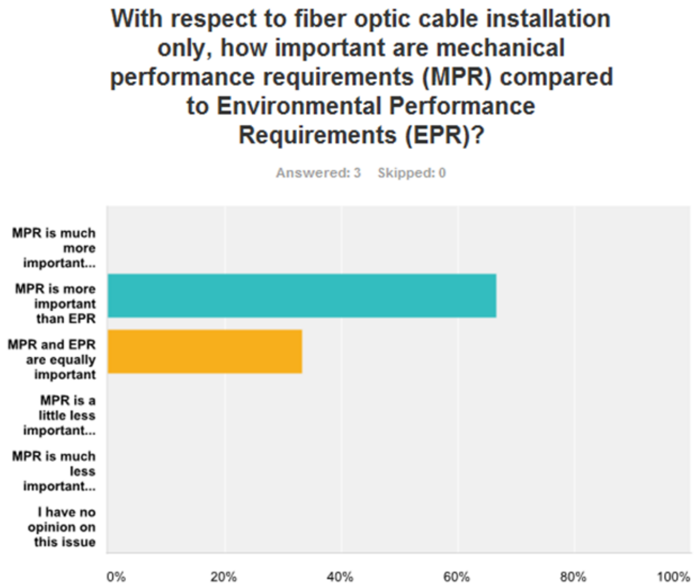
THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX B

Q1 Edit Question ▼ Add Question Logic Move Copy Delete

***1. With respect to fiber optic cable installation only, how important are mechanical performance requirements (MPR) compared to Environmental Performance Requirements (EPR)?**

- ◯ MPR is much more important than EPR
- ◯ MPR is more important than EPR
- ◯ MPR and EPR are equally important
- ◯ MPR is a little less important than EPR
- ◯ MPR is much less important than EPR
- ◯ I have no opinion on this issue



Answer Choices	Responses	
MPR is much more important than EPR	0%	0
MPR is more important than EPR	66.67%	2
MPR and EPR are equally important	33.33%	1
MPR is a little less important than EPR	0%	0
MPR is much less important than EPR	0%	0
I have no opinion on this issue	0%	0
Total		3

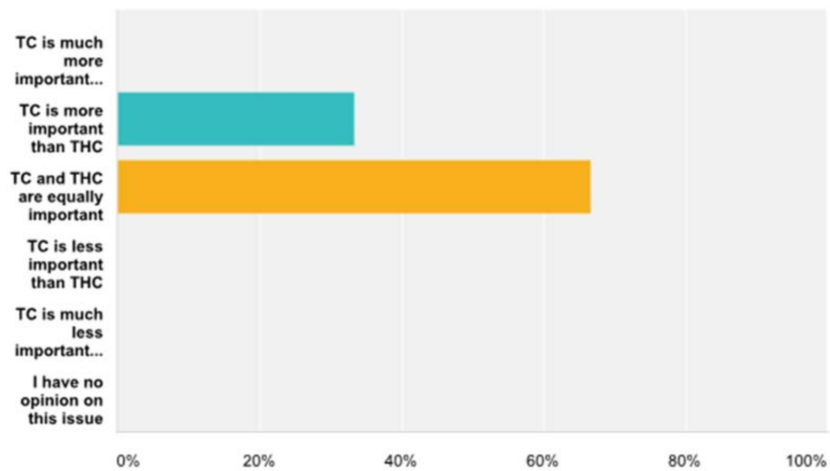
Q2 Edit Question ▼ Add Question Logic Move Copy Delete

***2. With respect to fiber optic cable installation only, how important are temperature cycling (TC) specifications compared to temperature humidity cycling (THC) specifications?**

- TC is much more important than THC
- TC is more important than THC
- TC and THC are equally important
- TC is less important than THC
- TC is much less important than THC
- I have no opinion on this issue

With respect to fiber optic cable installation only, how important are temperature cycling (TC) specifications compared to temperature humidity cycling (THC) specifications?

Answered: 3 Skipped: 0



Answer Choices	Responses	
TC is much more important than THC	0%	0
TC is more important than THC	33.33%	1
TC and THC are equally important	66.67%	2
TC is less important than THC	0%	0
TC is much less important than THC	0%	0
I have no opinion on this issue	0%	0
Total		3

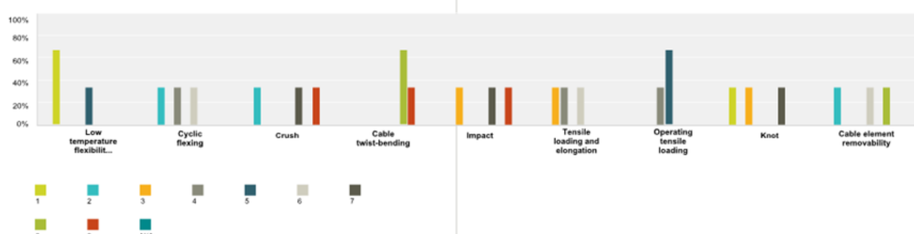
Q3 Edit Question ▼ Move Copy Delete

***3. With respect to fiber optic cable installation only, indicate the relative importance of the following mechanical performance requirements (MPR). Assign 10 points to the most important MPR. Relative to the most important MPR, on a scale of 0 (no importance) to 10 (most important) assign points to the remaining MPRs to indicate their relative importance.**

- Low temperature flexibility (cold bend) — N/A
- Cyclic flexing — N/A
- Crush — N/A
- Cable twist-bending — N/A
- Impact — N/A
- Tensile loading and elongation — N/A
- Operating tensile loading — N/A
- Knot — N/A
- Cable element removability — N/A

With respect to fiber optic cable installation only, indicate the relative importance of the following mechanical performance requirements (MPR). Assign 10 points to the most important MPR. Relative to the most important MPR, on a scale of 0 (no importance) to 10 (most important) assign points to the remaining MPRs to indicate their relative importance.

Answered: 3 Skipped: 0

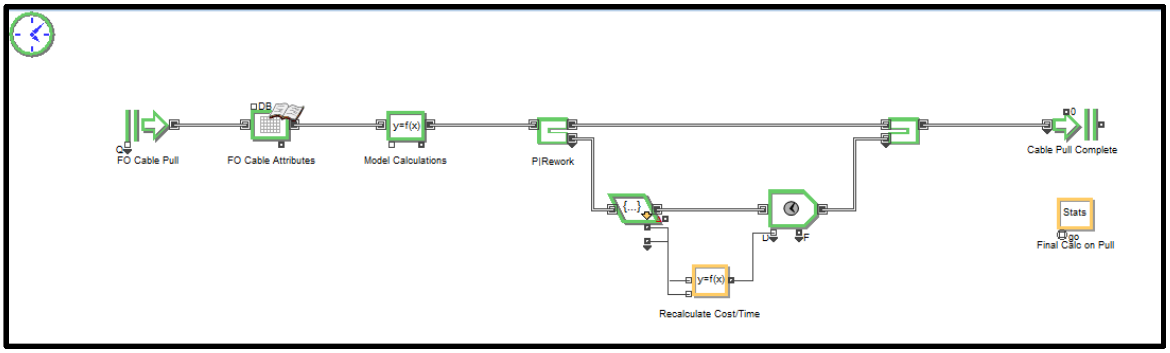


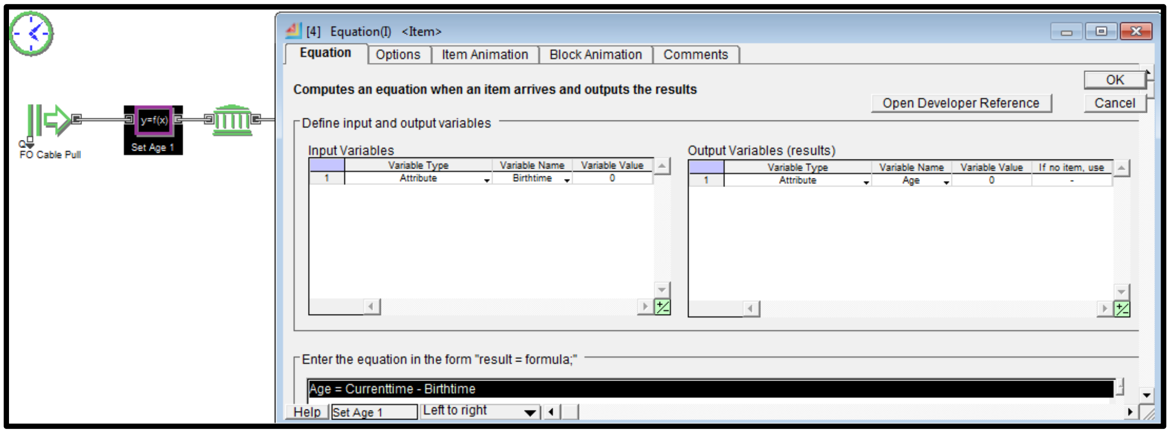
	1	2	3	4	5	6	7	8	9	N/A	Total	Average Ranking
Cable twist-bending	0% 0	0% 0	0% 0	0% 0	0% 0	0% 0	0% 0	66.67% 2	33.33% 1	0% 0	3	2.67
Impact	0% 0	0% 0	33.33% 1	0% 0	0% 0	0% 0	33.33% 1	0% 0	33.33% 1	0% 0	3	4.67
Crush	0% 0	33.33% 1	0% 0	0% 0	0% 0	0% 0	33.33% 1	0% 0	33.33% 1	0% 0	3	5.00
Cable element removability	0% 0	33.33% 1	0% 0	0% 0	0% 0	33.33% 1	0% 0	33.33% 1	0% 0	0% 0	3	5.67
Operating tensile loading	0% 0	0% 0	0% 0	33.33% 1	66.67% 2	0% 0	0% 0	0% 0	0% 0	0% 0	3	6.33
Tensile loading and elongation	0% 0	0% 0	33.33% 1	33.33% 1	0% 0	33.33% 1	0% 0	0% 0	0% 0	0% 0	3	6.67
Cyclic flexing	0% 0	33.33% 1	0% 0	33.33% 1	0% 0	33.33% 1	0% 0	0% 0	0% 0	0% 0	3	7.00
Knot	33.33% 1	0% 0	33.33% 1	0% 0	0% 0	0% 0	33.33% 1	0% 0	0% 0	0% 0	3	7.33
Low temperature flexibility (cold bend)	66.67% 2	0% 0	0% 0	0% 0	33.33% 1	0% 0	0% 0	0% 0	0% 0	0% 0	3	8.67

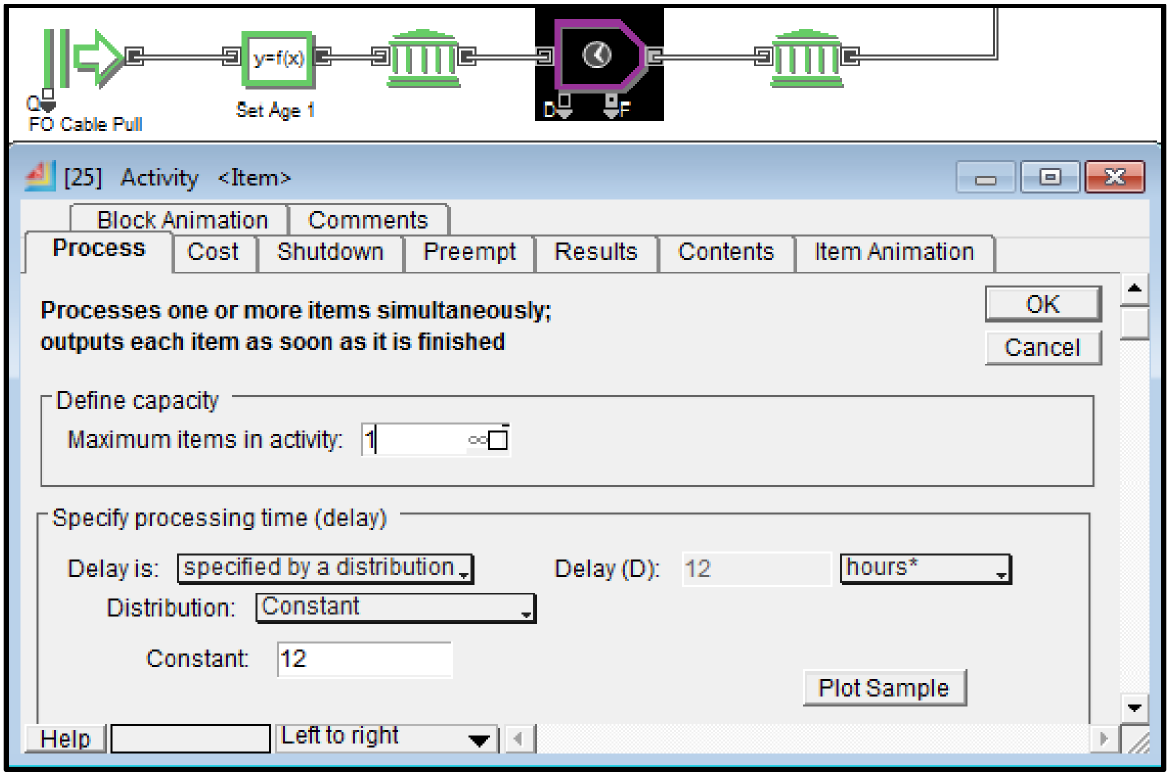
THIS PAGE INTENTIONALLY LEFT BLANK

APPENDIX C

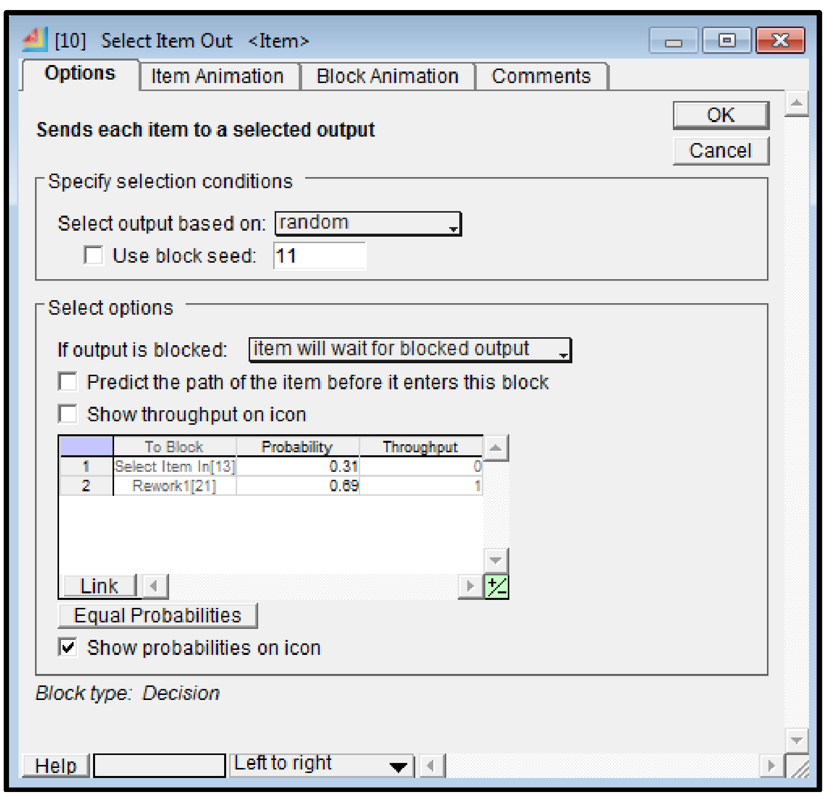
The following are iterations of the simulation model from ExtendSim:



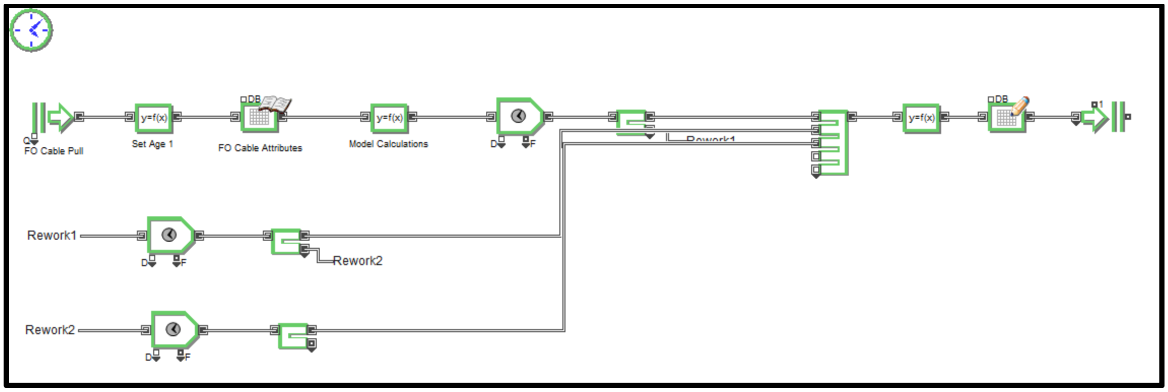


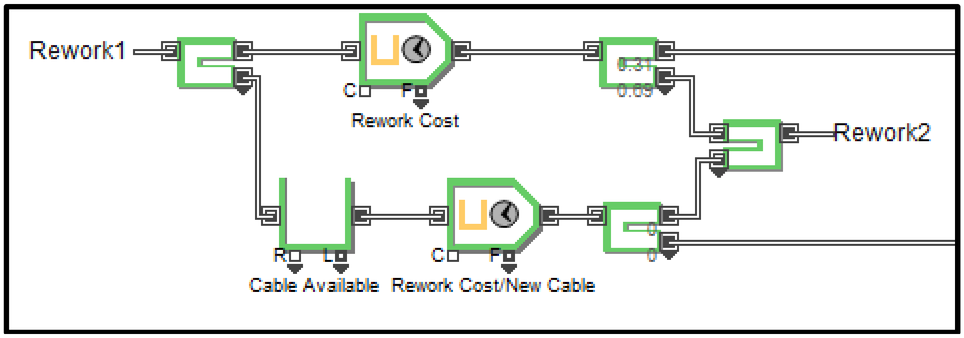


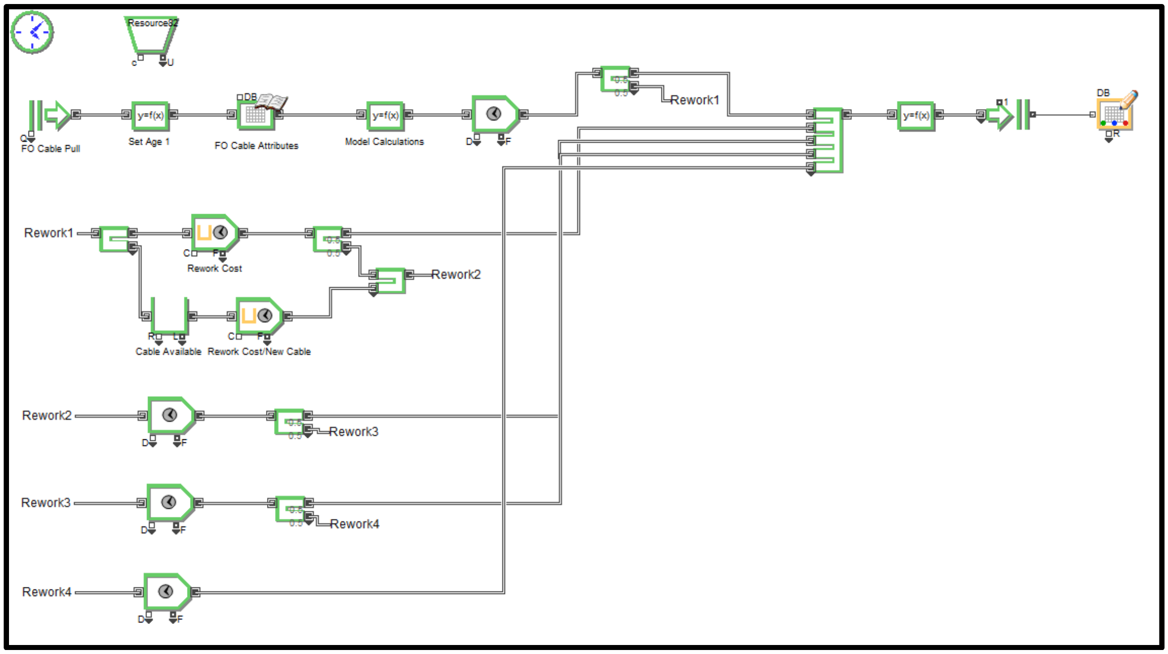
FO Cable Pull
y=f(x)
Set Age 1
D
F
[25] Activity <Item>
Block Animation
Comments
Process
Cost
Shutdown
Preempt
Results
Contents
Item Animation
Processes one or more items simultaneously;
outputs each item as soon as it is finished
OK
Cancel
Define capacity
Maximum items in activity: 1
Specify processing time (delay)
Delay is: specified by a distribution
Delay (D): 12
hours*
Distribution: Constant
Constant: 12
Plot Sample
Help
Left to right

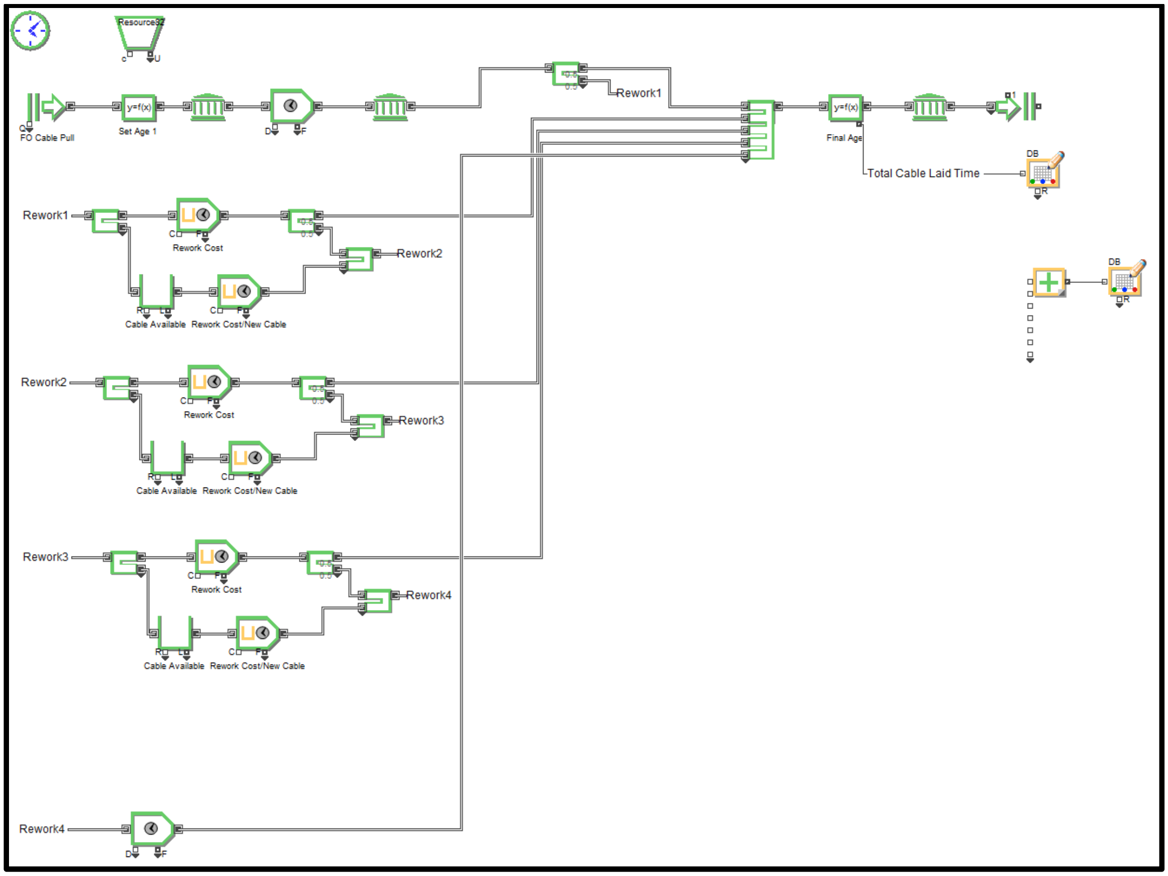


[10] Select Item Out <Item>
Options
Item Animation
Block Animation
Comments
Sends each item to a selected output
OK
Cancel
Specify selection conditions
Select output based on: random
Use block seed: 11
Select options
If output is blocked: item will wait for blocked output
Predict the path of the item before it enters this block
Show throughput on icon
To Block
Probability
Throughput
1
Select Item In[13]
0.31
0
2
Rework1[21]
0.69
1
Link
Equal Probabilities
Show probabilities on icon
Block type: Decision
Help
Left to right

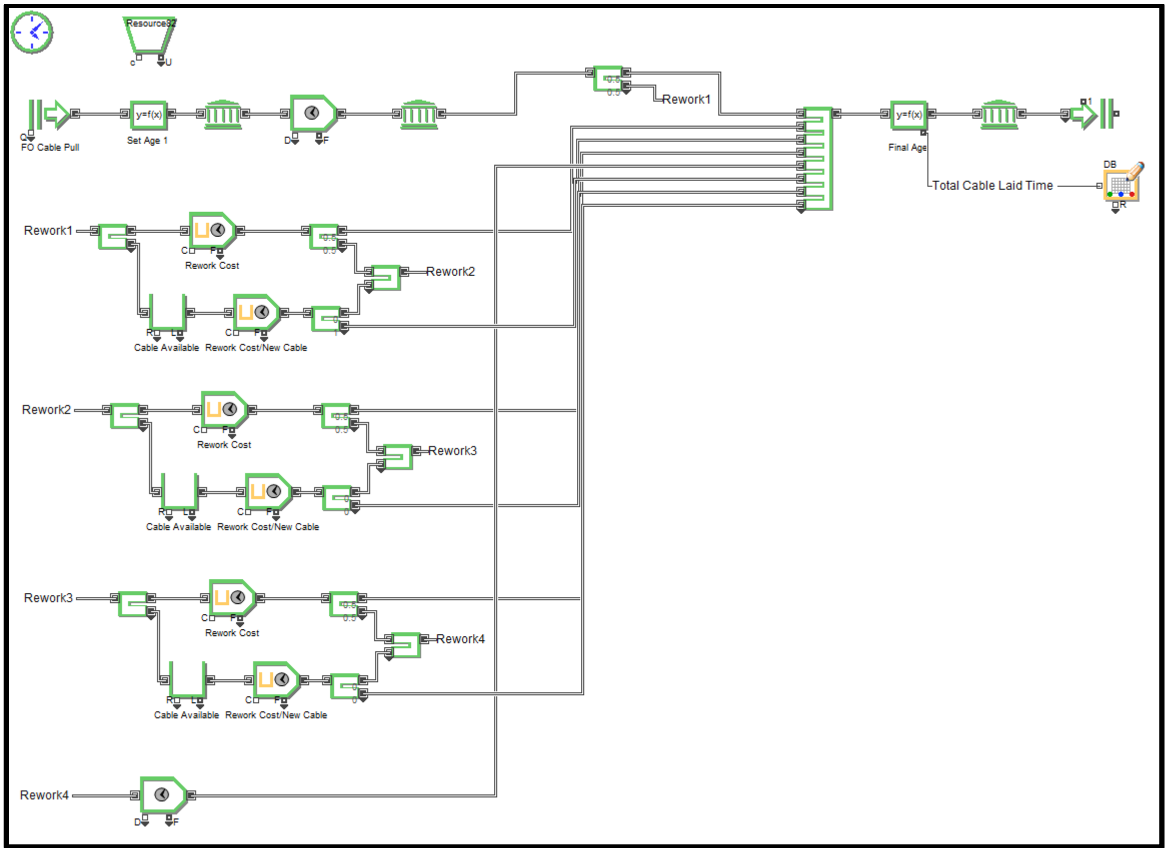

FO Cable Pull
Set Age 1
FO Cable Attributes
Model Calculations
Rework1
Rework1
Rework2
Rework2


Rework1
Rework Cost
Rework2
Cable Available
Rework Cost/New Cable

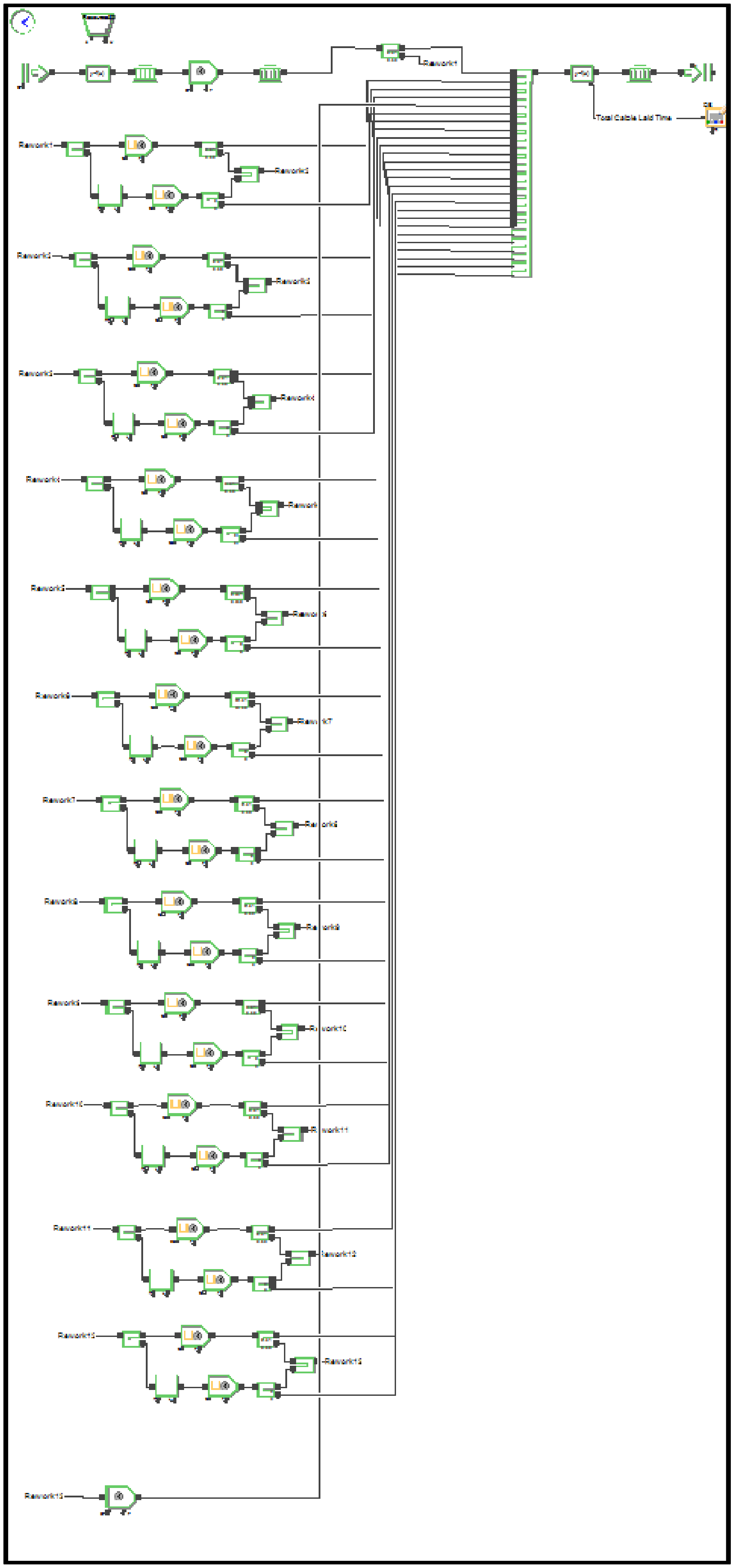

Resource32
FO Cable Pull
Set Age 1
FO Cable Attributes
Model Calculations
Rework1
Rework1
Rework Cost
Rework2
Cable Available
Rework Cost/New Cable
Rework2
Rework3
Rework3
Rework4
Rework4

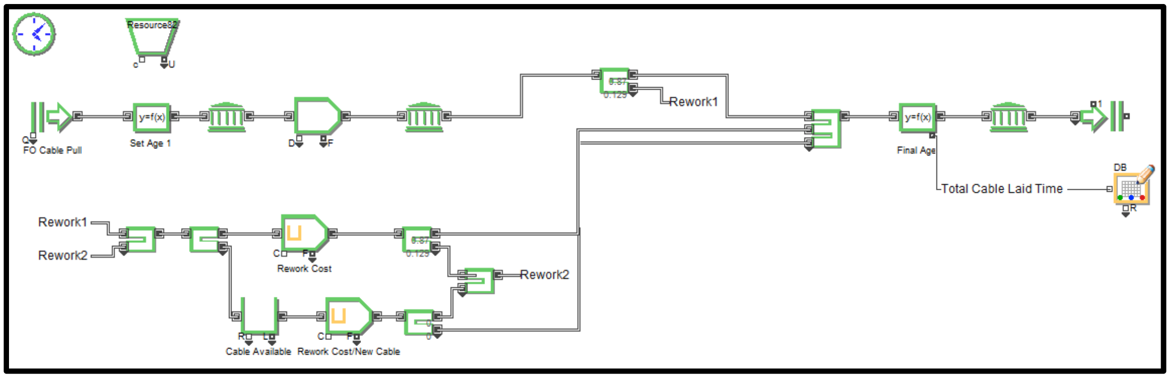


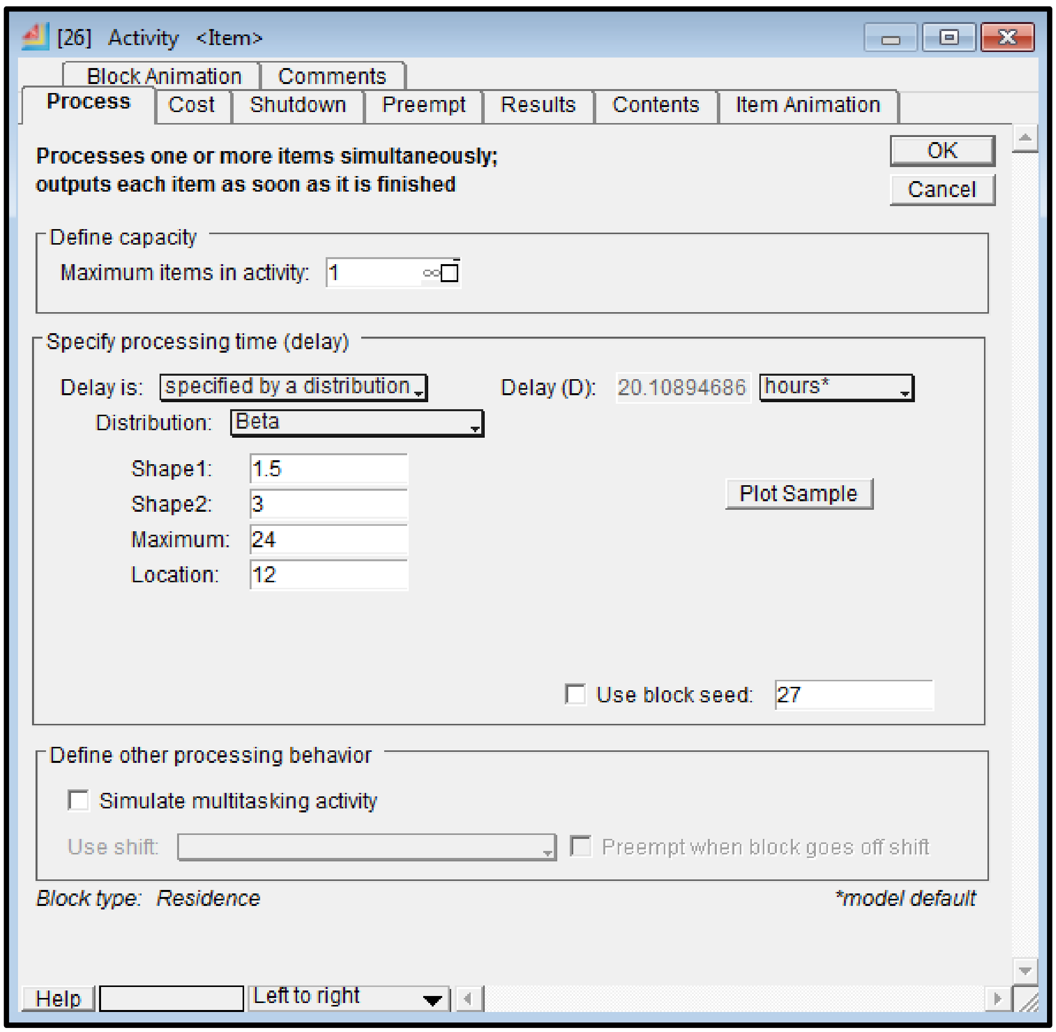
Resource32
FO Cable Pull
Set Age 1
Rework1
Final Age
Total Cable Laid Time
Rework1
Rework Cost
Rework2
Cable Available
Rework Cost/New Cable
Rework2
Rework Cost
Rework3
Cable Available
Rework Cost/New Cable
Rework3
Rework Cost
Rework4
Cable Available
Rework Cost/New Cable
Rework4

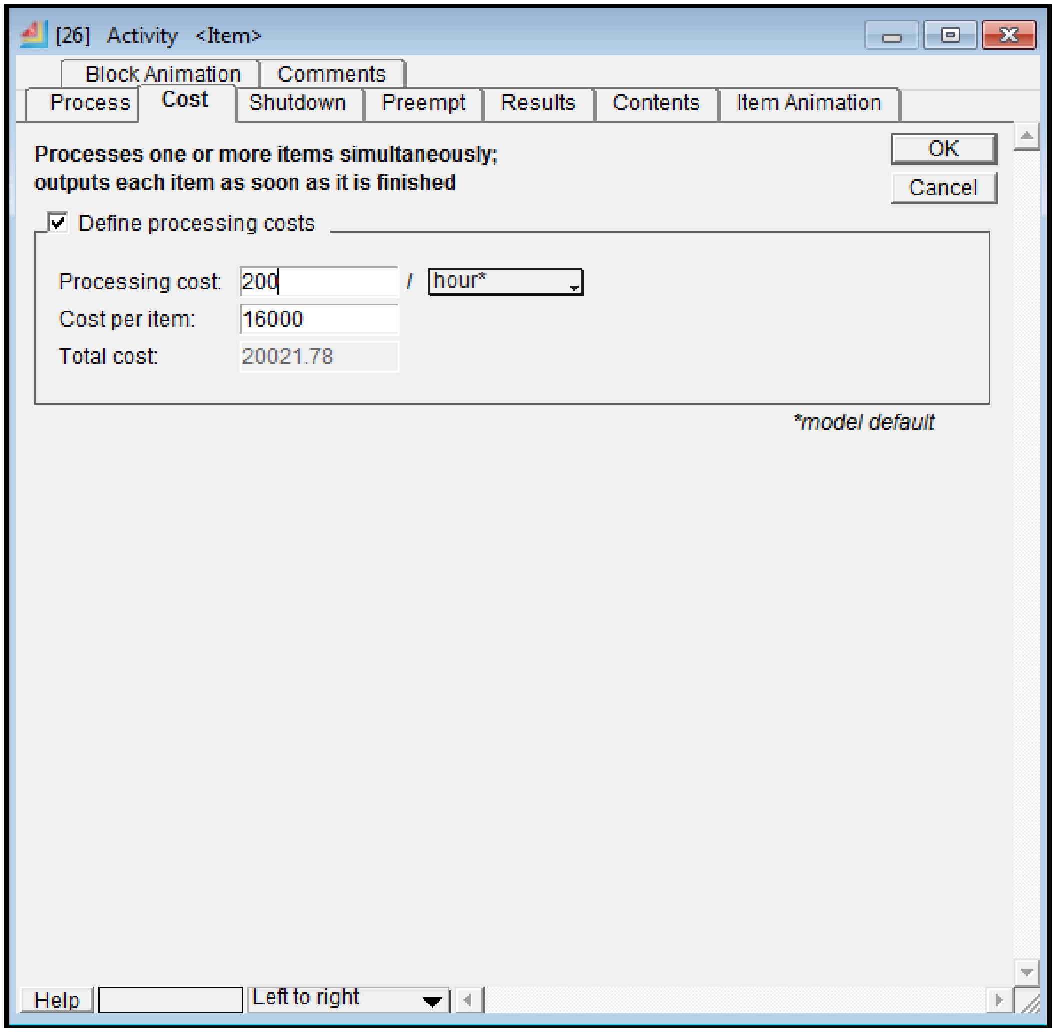


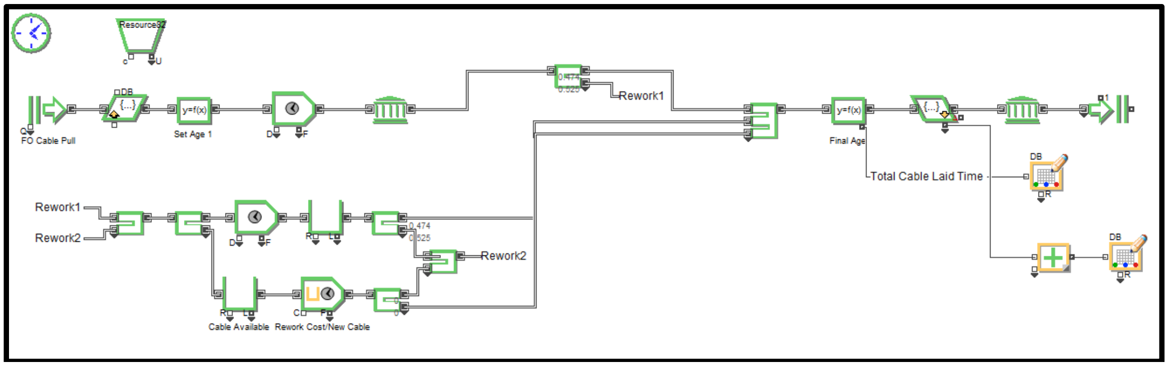
Resource32
FO Cable Pull
Set Age 1
Rework1
Final Age
Total Cable Laid Time
Rework1
Rework Cost
Rework2
Cable Available
Rework Cost/New Cable
Rework2
Rework Cost
Rework3
Cable Available
Rework Cost/New Cable
Rework3
Rework Cost
Rework4
Cable Available
Rework Cost/New Cable
Rework4


Rework1
Rework2
Rework3
Rework4
Rework5
Rework6
Rework7
Rework8
Rework9
Rework10
Rework11
Rework12
Rework13
Total Cable Laid Time


FO Cable Pull
Set Age 1
Rework1
Final Age
Total Cable Laid Time
Rework1
Rework2
Rework Cost
Rework2
Cable Available
Rework Cost/New Cable


[26] Activity <Item>
Block Animation
Comments
Process
Cost
Shutdown
Preempt
Results
Contents
Item Animation
Processes one or more items simultaneously;
outputs each item as soon as it is finished
OK
Cancel
Define capacity
Maximum items in activity: 1
Specify processing time (delay)
Delay is: specified by a distribution
Delay (D): 20.10894686
hours*
Distribution: Beta
Shape1: 1.5
Shape2: 3
Maximum: 24
Location: 12
Plot Sample
Use block seed: 27
Define other processing behavior
Simulate multitasking activity
Use shift:
Preempt when block goes off shift
Block type: Residence
*model default
Help
Left to right


[26] Activity <Item>
Block Animation
Comments
Process
Cost
Shutdown
Preempt
Results
Contents
Item Animation
OK
Cancel
Processes one or more items simultaneously;
outputs each item as soon as it is finished
Define processing costs
Processing cost: 200 / hour*
Cost per item: 16000
Total cost: 20021.78
*model default
Help
Left to right


FO Cable Pull
Set Age 1
Rework1
Final Age
Total Cable Laid Time
Rework1
Rework2
Rework2
Cable Available
Rework Cost/New Cable

LIST OF REFERENCES

Anonymous Person A. 2012. “Cable Pulling Subject Matter Expert.”

Arena, Mark V. 2006. *Why Has the Cost of Navy Ships Risen?: A Macroscopic Examination of the Trends in U.S. Naval Ship Costs Over the Past Several Decades*. Santa Monica: Rand.

Solitario, William. 2009. “Design for Produciblity” (PowerPoint presentation). November 24.

Bold, Norbert T., Martin Wapner, and Luther M. Blackwell. 1976. “Shipboard Data Multiplex System (sdms)—a New Design for Lower Ship Cost and Improved Flexibility.” *Naval Engineers Journal* 88, no.2: 245–256.

Cables Plus USA. “Guidelines for Installation of Fiber-optic Cables”. http://www.cablesplususa.com/pdf/Fiber-Installation-Guide.pdf.

Carstensen, Russell V. 1978. “A Cost Estimating Routine for Electric Cable Installation on Naval Ships.” *Naval Engineers Journal* 90, no.6: 81–86.

Dokkum, Klaas Van. 2005. *Ship Knowledge Covering Ship Design Construction and Operation*. 2nd ed.. Amsterdam: DOKMAR.

Hayes, Jim, and Fiber-optic Association. 2009. *FOA Reference Guide to Fiber-optics: Study Guide to FOA Certification*. Fallbrook: BookSurge.

Hayter, Anthony J. 2006. *Probability and Statistics for Engineers and Scientists*. 3rd ed. Belmont: Duxbury.

Hendricks, Verle, Jim Pokrywka, and Cliff Creek. 1988. “Wired for Disaster: Cableway Improvement Program (The National Shipbuilding Research Program)”. Paper presented at the annual meeting for the National Shipbuilding Research Program, Seattle, Washington, August 24–26, 1988.

Jolliff, James V. 1974. “Modular Ship Design Concepts.” Naval Engineers Journal 86: 11–32.

Keeney, Ralph L. 1996. Value-focused Thinking: A Path to Creative Decisionmaking. Cambridge: Harvard University.

Kirkwood, Craig W. 1997. Strategic Decision Making: Multiobjective Decision Analysis with Spreadsheets. Belmont: Brooks/Cole.

Knudsen et al. 1990. “A Ship-Wide System Engineering Approach for Fiber-optics for Surface Combatants.” Naval Engineers Journal 102: 127–137.

Pirich, R., and J. Mazurowski. 2012. “Engineering of Fiber-optics Infrastructure.” Paper presented at the In Systems, Applications and Technology Conference, Farmingdale, New York, May 4, 2012.

Rapping, Leonard. 1965. “Learning and World War II Production Functions.” The Review of Economics and Statistics 47: 81–86.

Sato, Shuji, and Shizuo Suzuki. 1989. “The National Shipbuilding Research Program. 1989 Ship Oroduction Symposium. Paper No. 9: IHI Zone Logic Application to Electrical Outfitting on Highly Sophisticated Ships”. Paper presented at the Ship Production Symposium, Arlington, Virginia, September 13-15, 1989.

Schiffauerova, Andrea, and Vince Thomson. 2006. “A Review of Research on Cost of Quality Models and Best Practices.” International Journal of Quality & Reliability Management 23: 647–669.

Smith, Vergil B. 1977. “Aircraft Carrier Electrical Power System Design Practices.” Naval Engineers Journal 89: 83–91.

Zubaly, Robert B. 1996. Applied Naval Architecture. Atglen: Schiffer.

INITIAL DISTRIBUTION LIST

1. Defense Technical Information Center
   Ft. Belvoir, Virginia

2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California